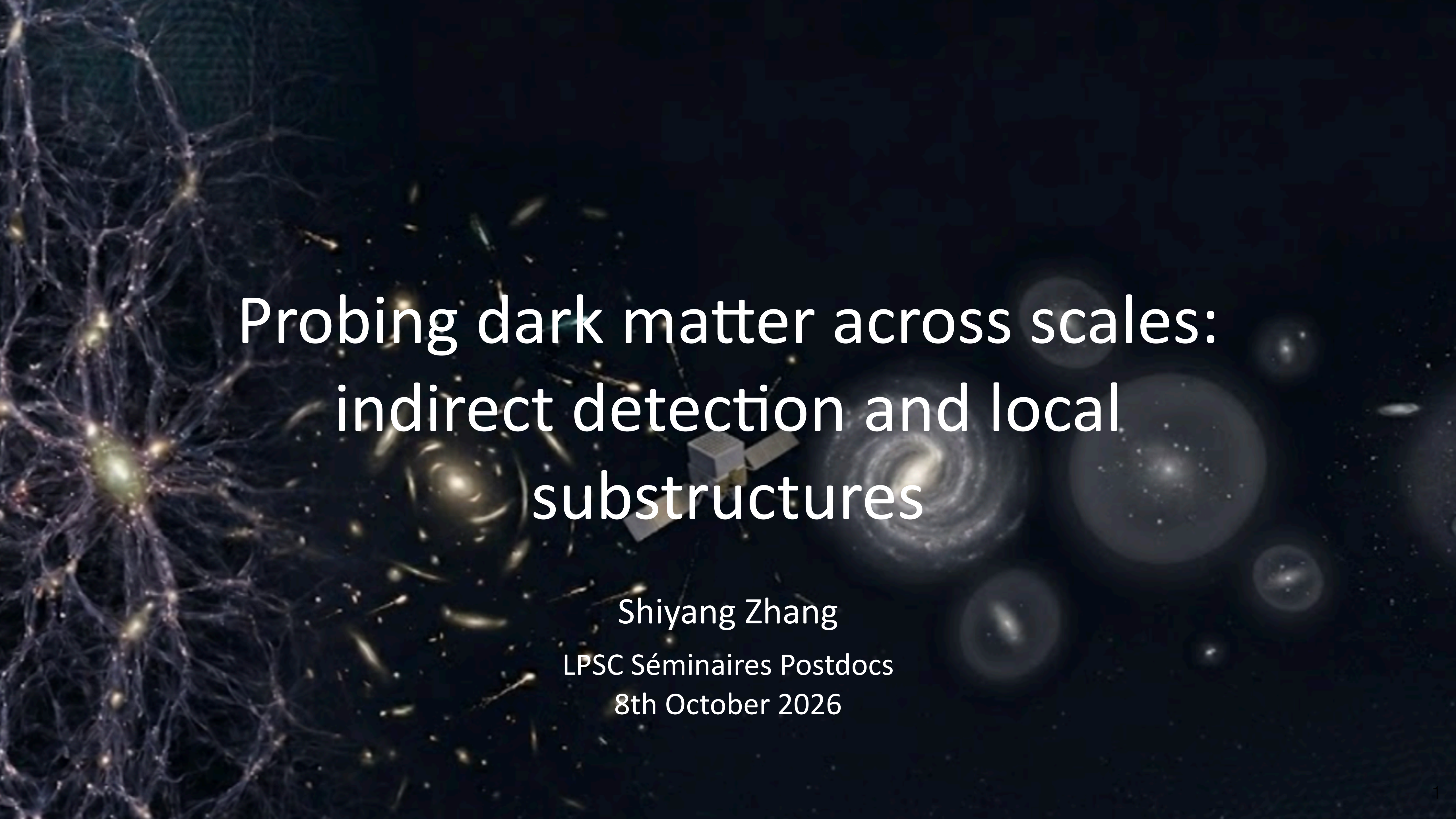


A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are depicted as thin, glowing purple and blue lines, while the clusters are represented by bright yellow and orange points. The background is a deep black space filled with numerous small, distant galaxies.

Probing dark matter across scales: indirect detection and local substructures

Shiyang Zhang

LPSC Séminaires Postdocs

8th October 2026

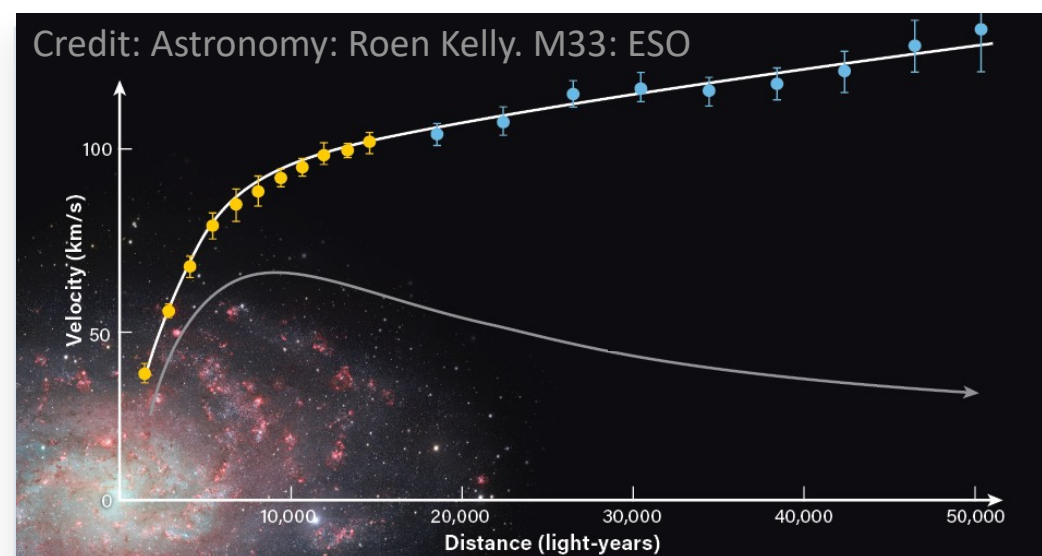
Dark Matter (DM): what, why, and how

Map where it is with gravity; test what it could be with gamma rays

● Dark Energy 68.3% ● Dark Matter 26.8% ● Ordinary Matter 4.9%

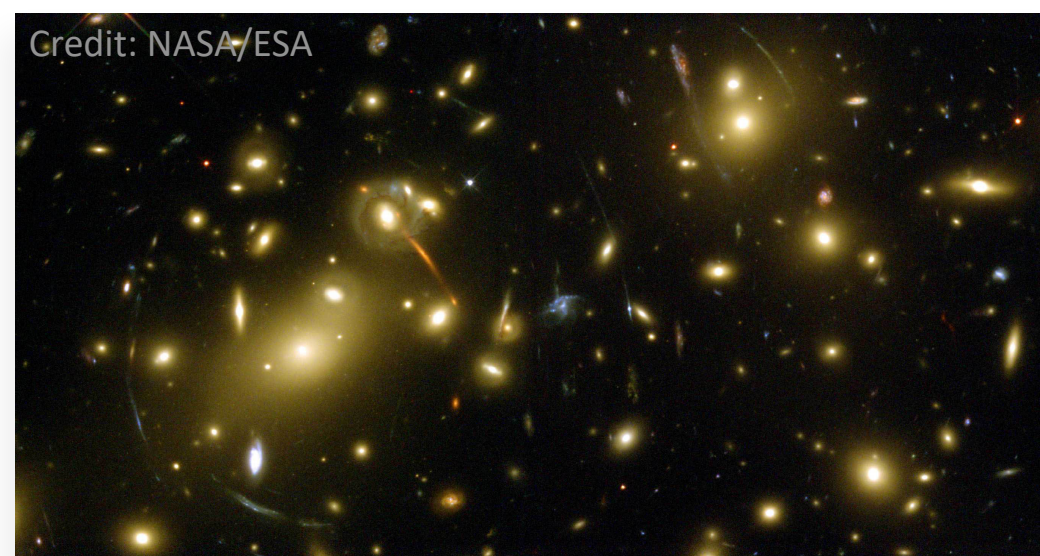


GRAVITATIONAL EVIDENCE FOR DARK MATTER



Galaxy rotation curves

Stars orbit too fast at large radii



Gravitational lensing

Light bent by unseen mass



Galaxy cluster collisions

DM passes through (blue); gas collides (pink)

WHAT is dark matter?

A non-luminous, gravity-only form of matter. It does not emit, absorb, or scatter light, and its microscopic nature remains unknown.

WHY does it matter?

Cosmological abundance: DM makes up ~27% of the total energy content of the Universe, and ~85% of all matter.

HOW do we know it is there?

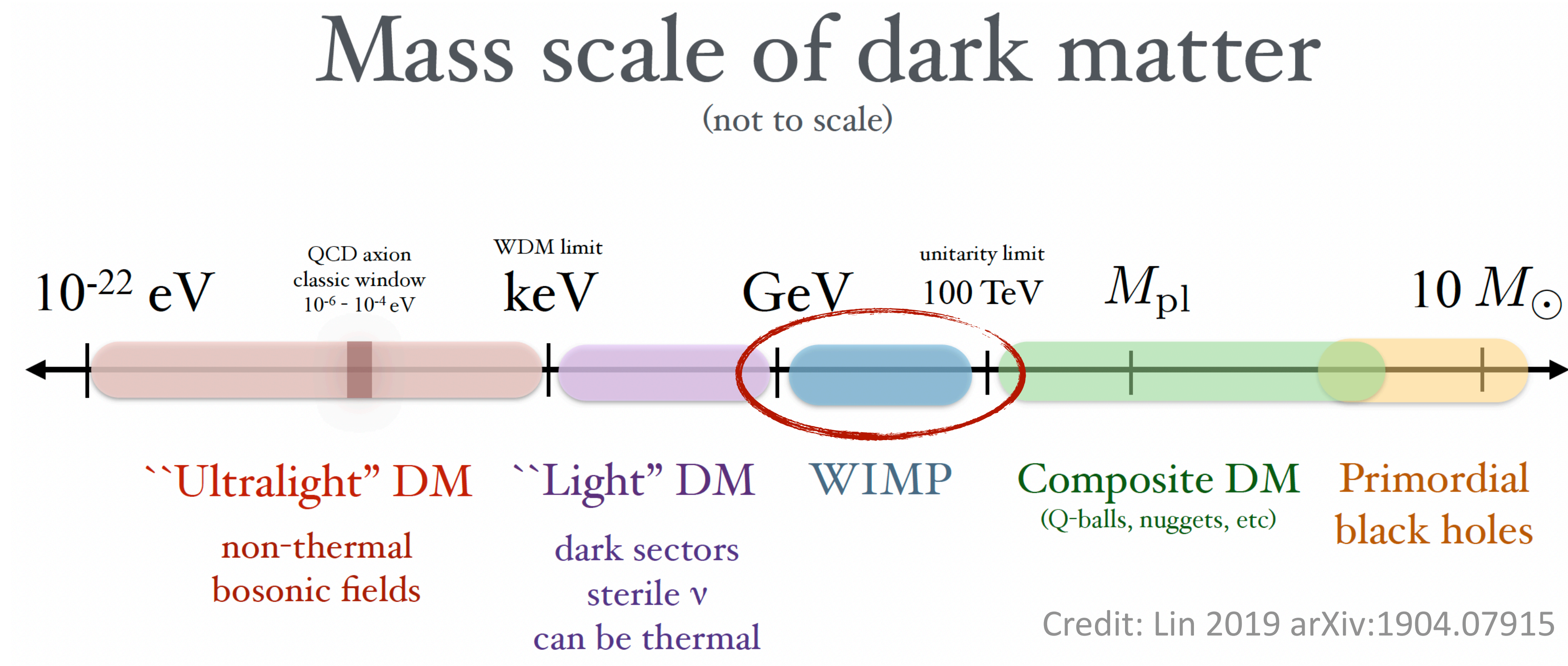
The evidence comes from several observations: galaxy rotation curves, gravitational lensing, galaxy cluster, and the large-scale distribution of galaxies.

Visible matter alone is not enough!

Outline

- DM candidates and indirect searching
- Motivation: probing DM across scales
 - Large scales: weak lensing x gamma rays
 - Local scales: study ultra-faint dwarf galaxies (UFDs) and the their survey selection effects
- Bridging scales for DM searches
- Conclusions

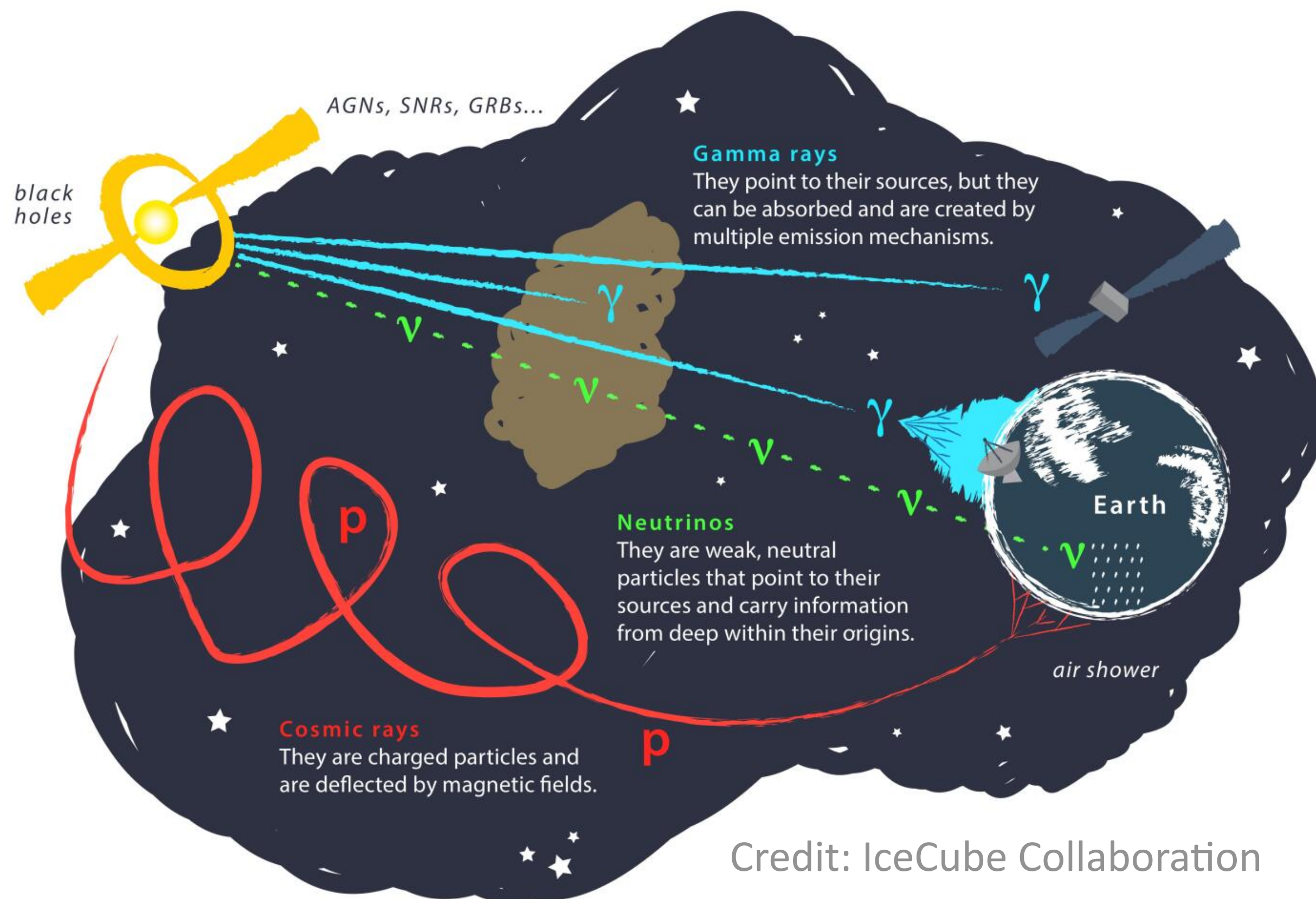
Theoretical frameworks: WIMPs and indirect searching



- Weakly Interacting Massive Particle (WIMP) is a well-motivated DM candidate
- “WIMP miracle”: the natural annihilation rate during thermal freeze-out predicts a present-day DM density matches cosmological observations

Theoretical frameworks: WIMPs interactions & indirect searching

Indirect searches look for Standard Model particles produced by DM annihilation or decay.



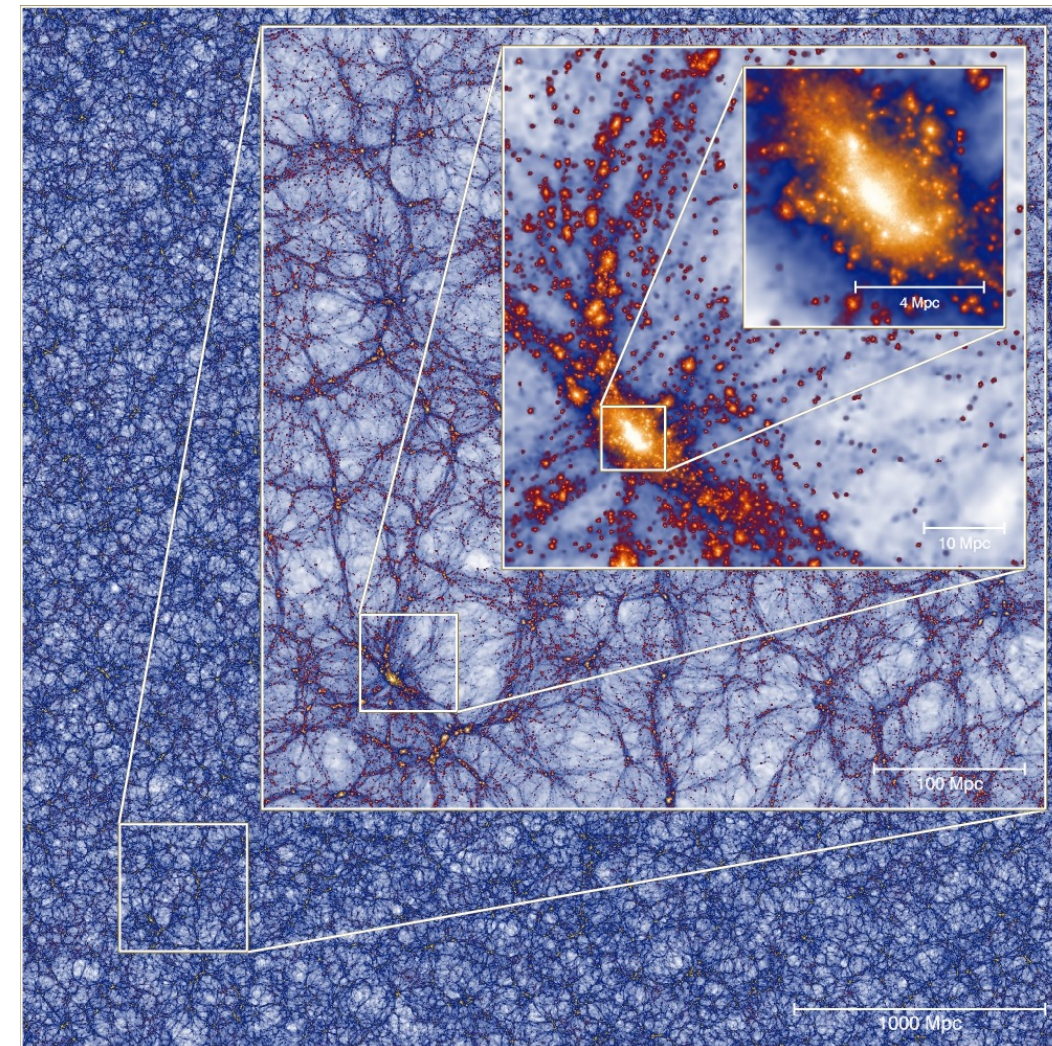
- **Annihilation:** annihilation cross-section
 $\langle \sigma_{\text{ann}} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$
- **Decay:** decay rate (lifetime)
 $\Gamma \sim 10^{-28} - 10^{-26} \text{ s}^{-1}$

Motivation: probing WIMP DM across scales

If WIMPs annihilate or decay, where should we look for gamma-ray signatures?

Large-scale structure

Cross-correlate mass tracers with gamma-ray emission



Credit: Millennium-XXL

Weak lensing

traces projected mass

Unresolved Gamma-Ray Background (UGRB)

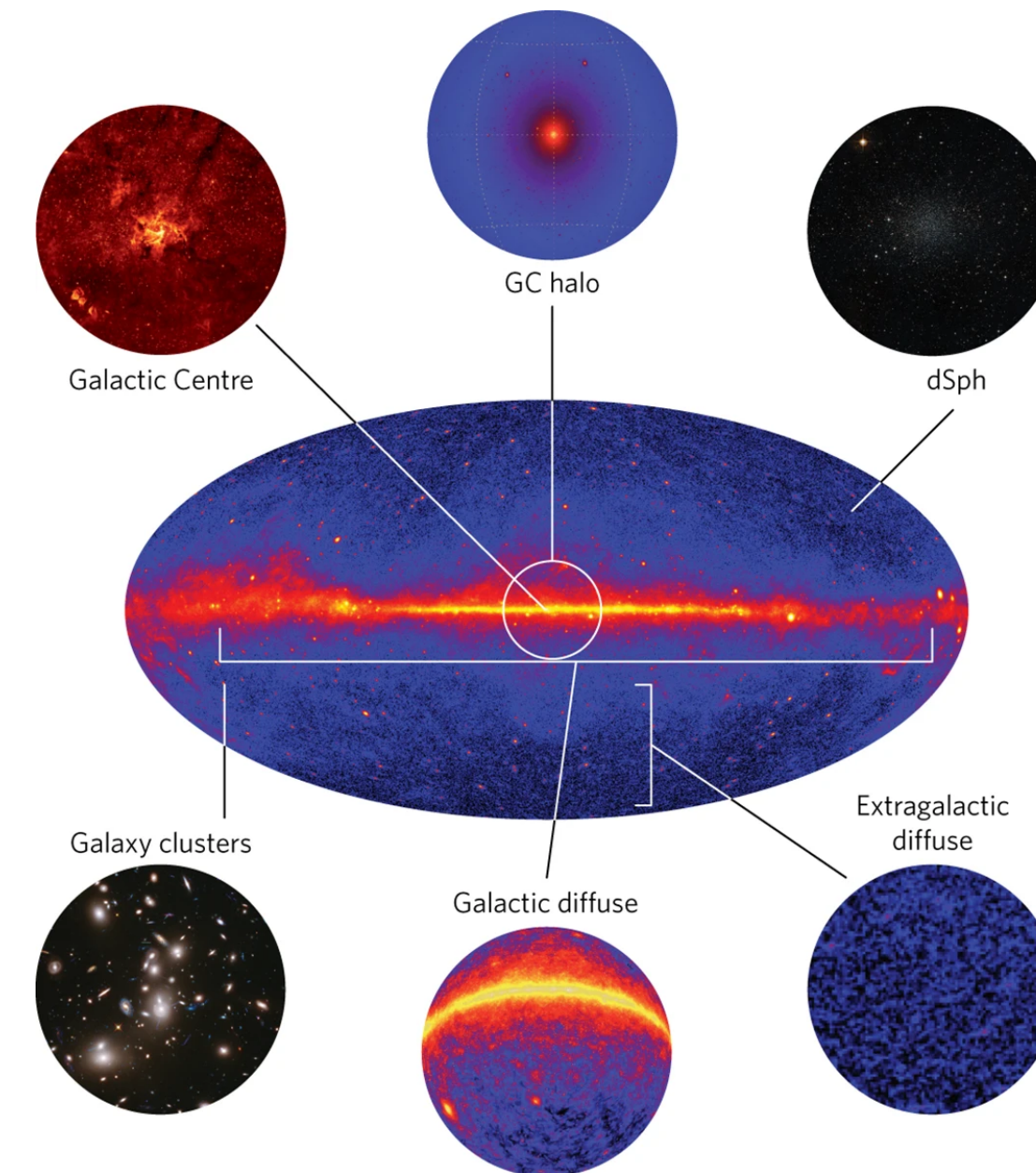
contains the potential signal from WIMPs interaction

Cross-correlation

gamma-ray maps should trace the same large-scale structure as the projected mass

Local substructure

Find and characterise DM-dominated targets



Credit: Q.D. Wang; DSS2; Fermi LAT Collaboration; STScI

Why ultra faint dwarf satellites?

nearby, faintest, DM-dominated

Better target lists improve indirect searches

more & better-characterised dwarfs tighten the DM properties constraints

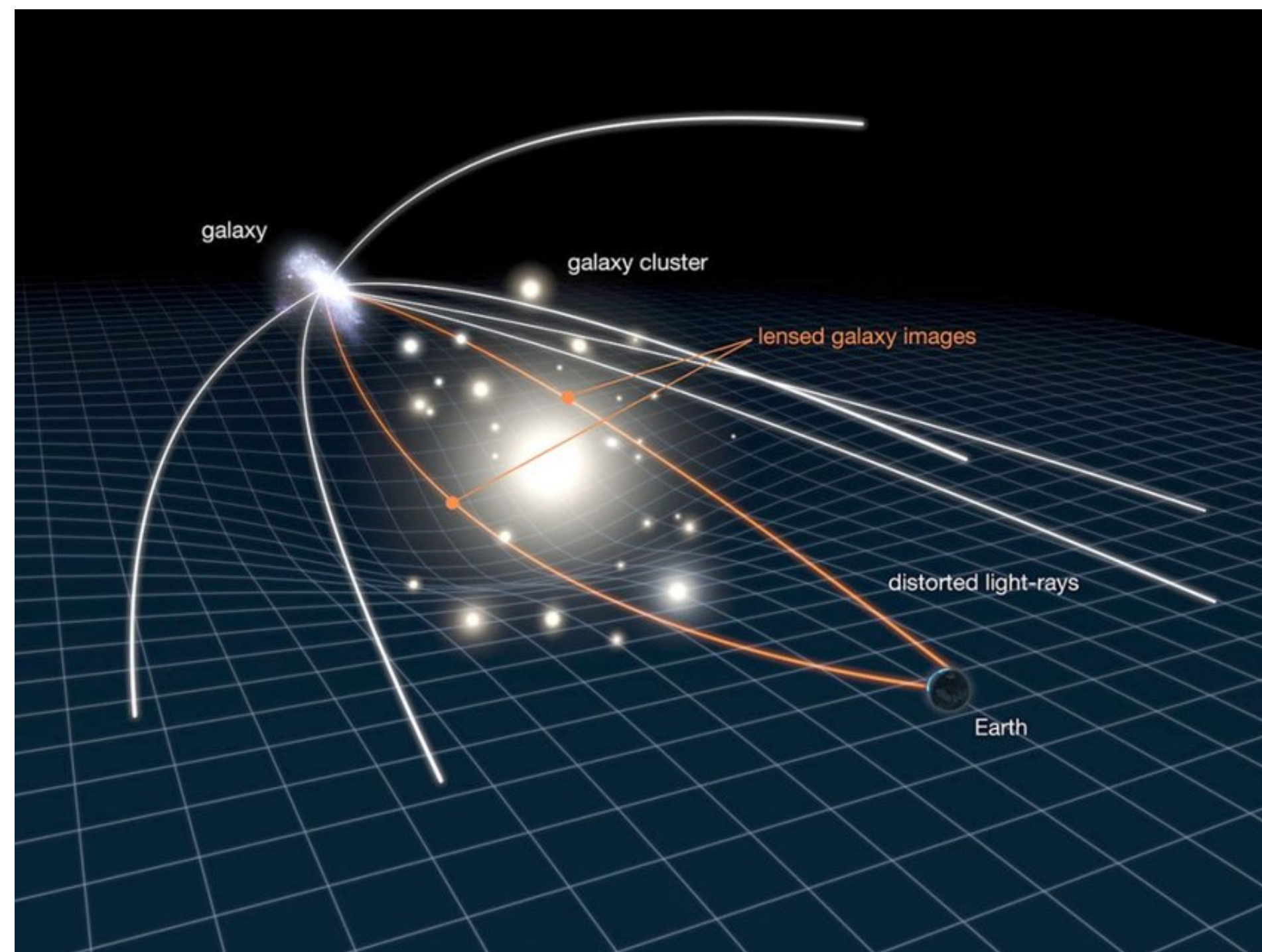
Cosmological statistics + local target discovery → reliable indirect DM searches

Large-scale DM searches: Weak lensing as a mass tracer

Small coherent distortions of galaxy shapes reveal the projected mass distribution

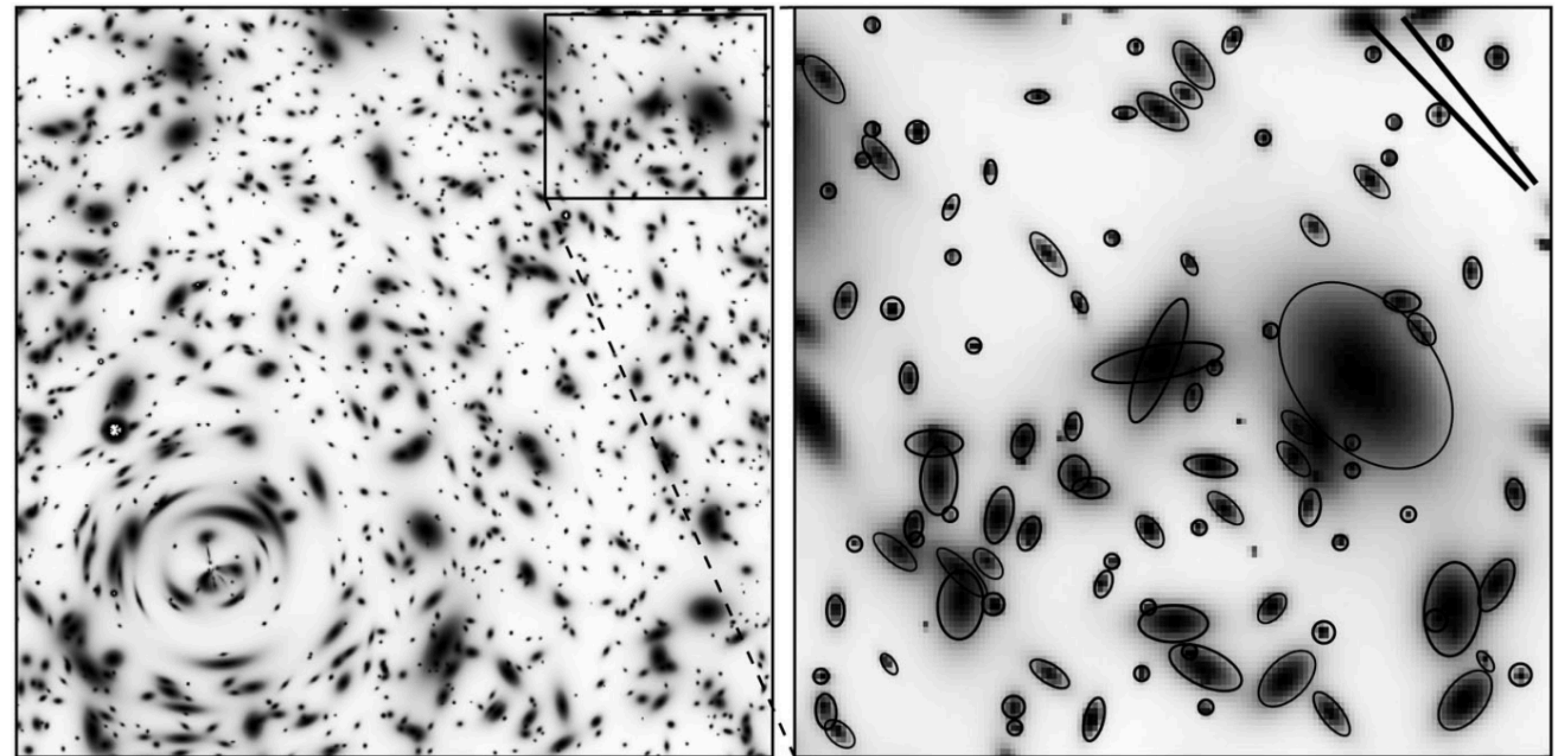
Gravitational lensing: The light from distant galaxies is slightly deflected by the matter distribution along the line of sight.

Why weak lensing? Direct map of the mass distribution



Credit: NASA, ESA & L. Calçada

Weak lensing

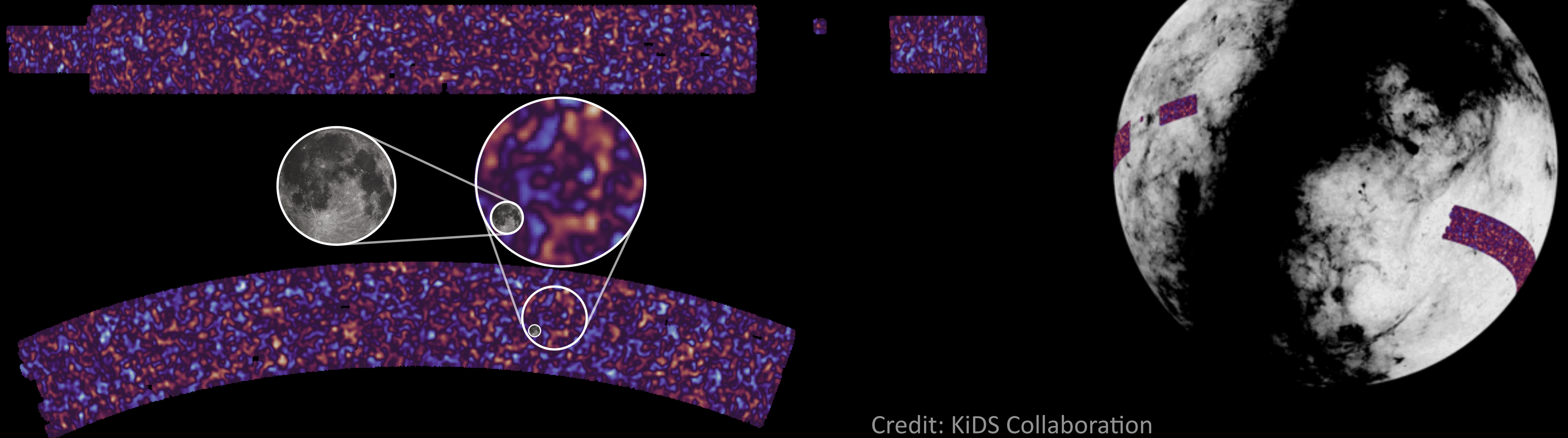


Strong lensing

Credit: Mellier, Y. 1999

Data: KiDS-Legacy & weak lensing

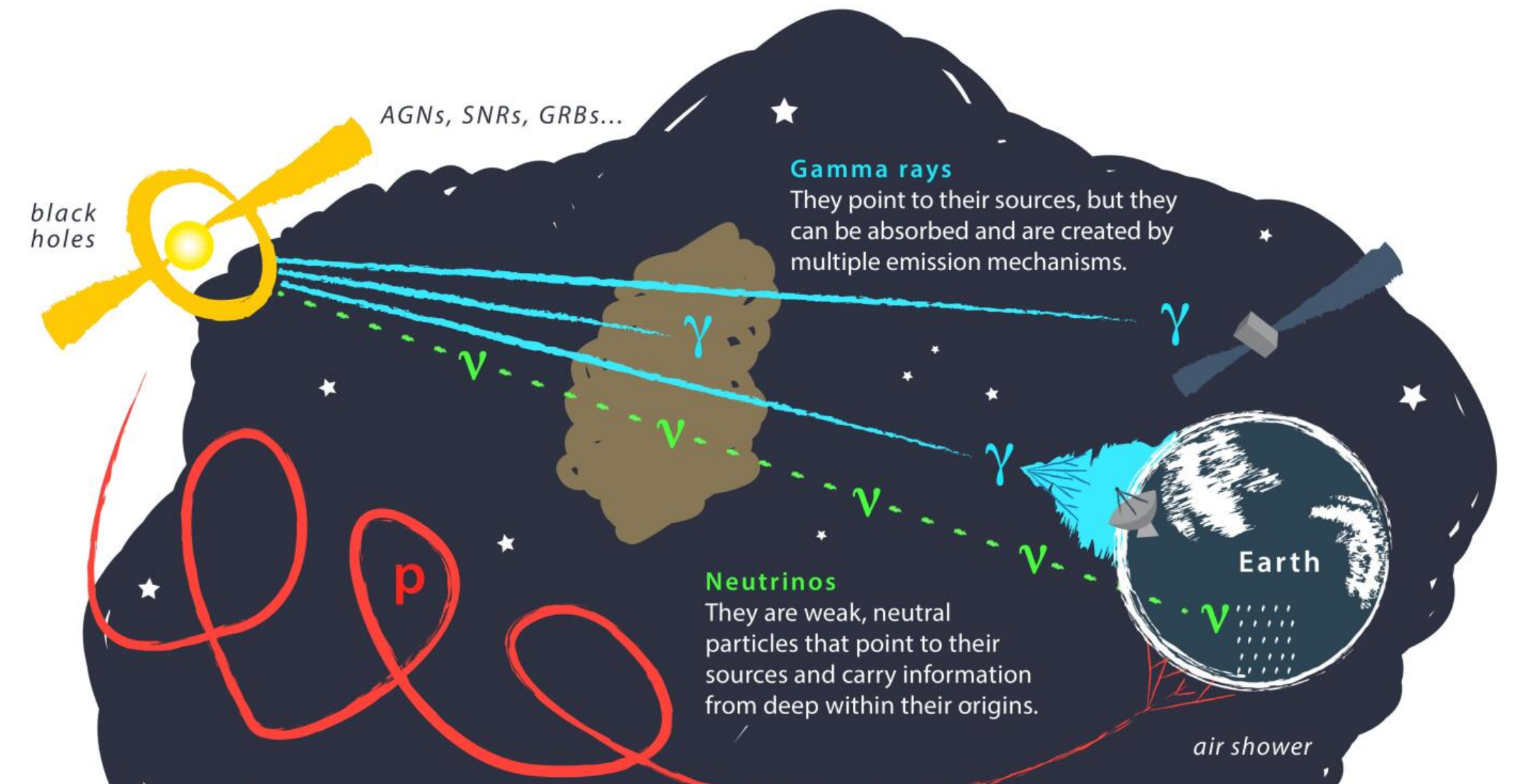
- Wide-field optical weak-lensing survey
- 1350 deg² total, 967.4 deg² effective area with ~41 million galaxies
- Excellent image quality: mean r-band seeing ~0.7''
- Multi-band photometry (9+1 bands) + calibration data for robust photo-z and tomography



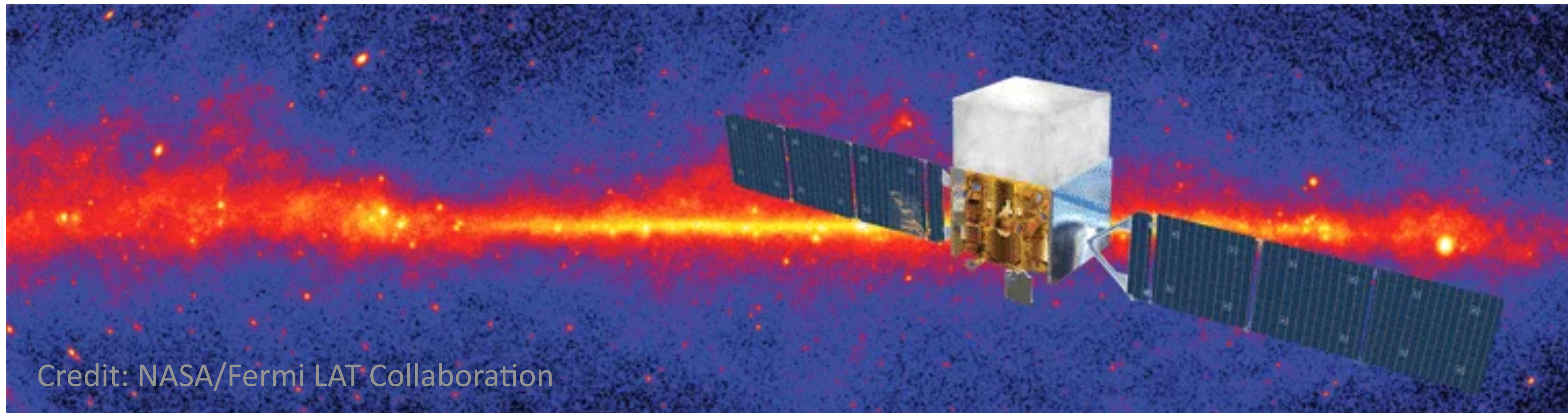
Credit: KiDS Collaboration

Data: Fermi Large Area Telescope (LAT)

- Space-based gamma-ray telescope, since 2008
- Energy range: ~ 20 MeV to >300 GeV
- Ideal for diffuse GeV gamma-ray mapping
- Complementary to ground-based telescopes:
 - ground-based: very-higher-energy air-shower detection
 - Fermi-LAT: wide-field, uniform sky coverage



Credit: IceCube Collaboration

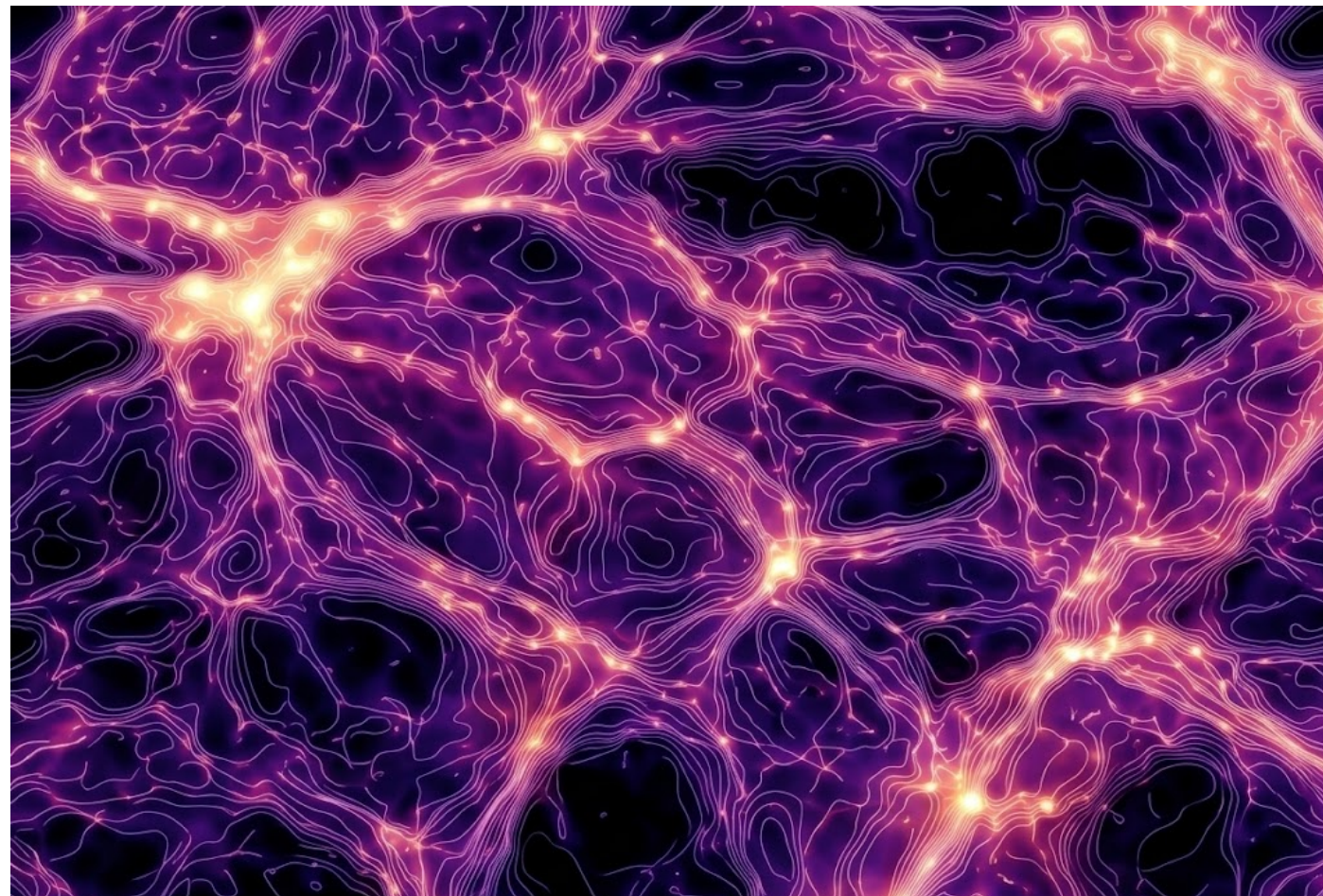


Credit: NASA/Fermi LAT Collaboration

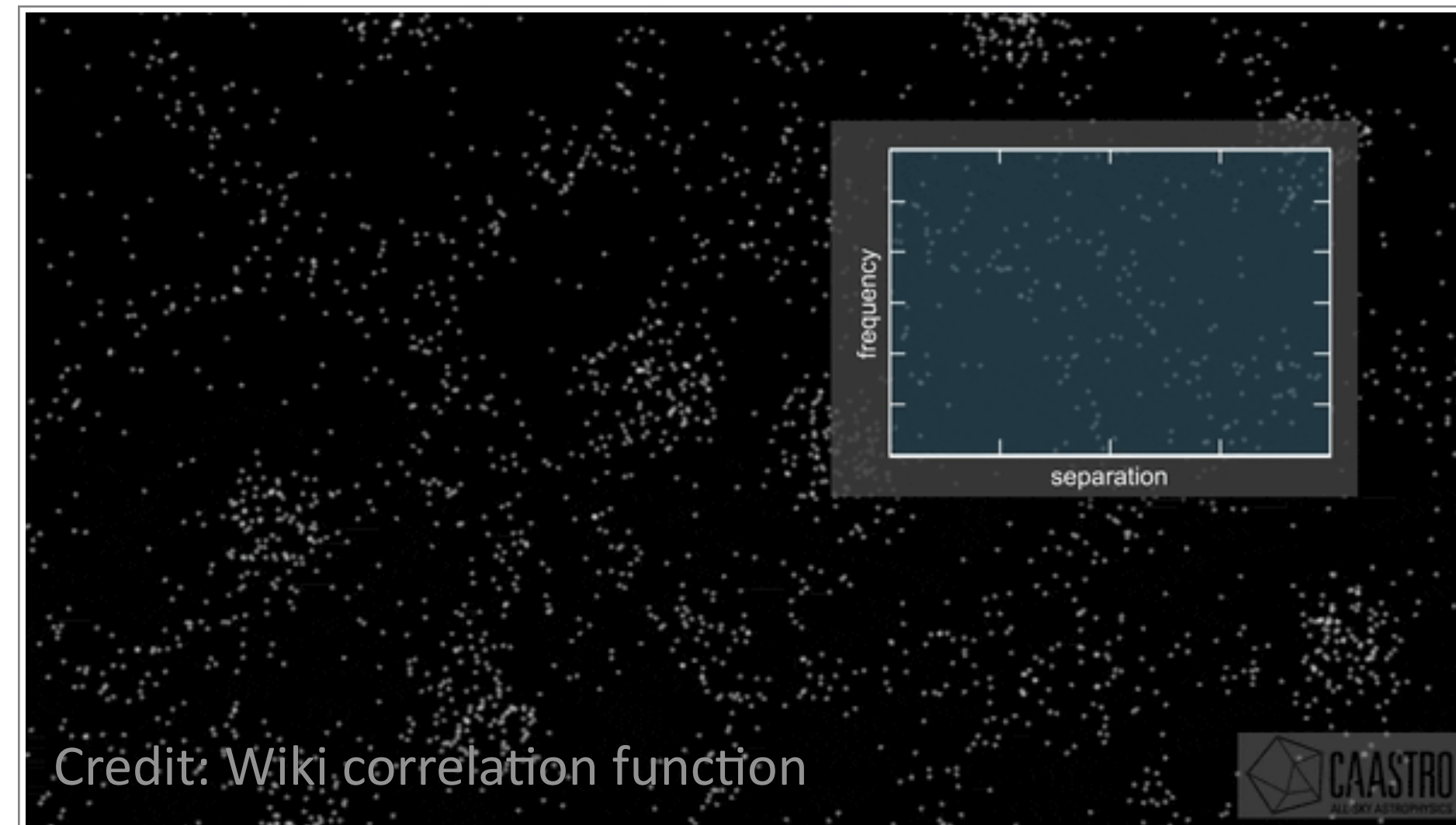
Large-scale DM searches: weak lensing $\times$ gamma rays

If DM contributes to the gamma-ray background, its signal should be statistically correlated with the mass distribution

Weak-lensing map



**Unresolved Gamma-Ray
Background (UGRB)**



Two-point correlation

Statistical inference

Measured C_ℓ (UGRB $\times$ WL)

Two-point angular cross-power spectrum from data



Model prediction

DM annihilation / decay + astrophysical backgrounds



Likelihood fit

Vary the DM parameter and find the model most consistent with the measured C_ℓ



DM constraints

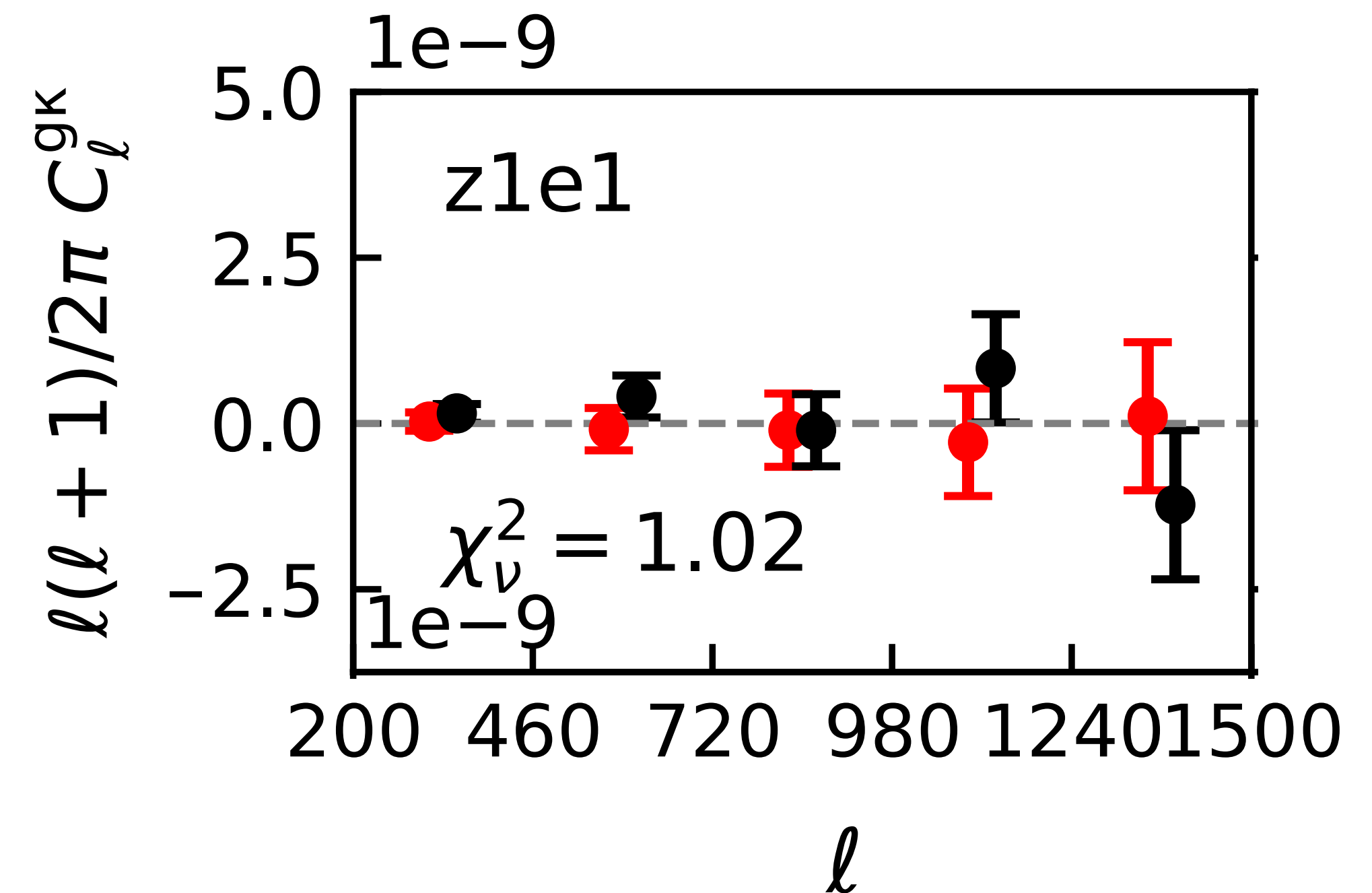
upper limits on $\langle \sigma_{\text{ann}} v \rangle$ or Γ_{dec}

Result: cross-correlation measurements

Black for E-mode

Red for B-mode

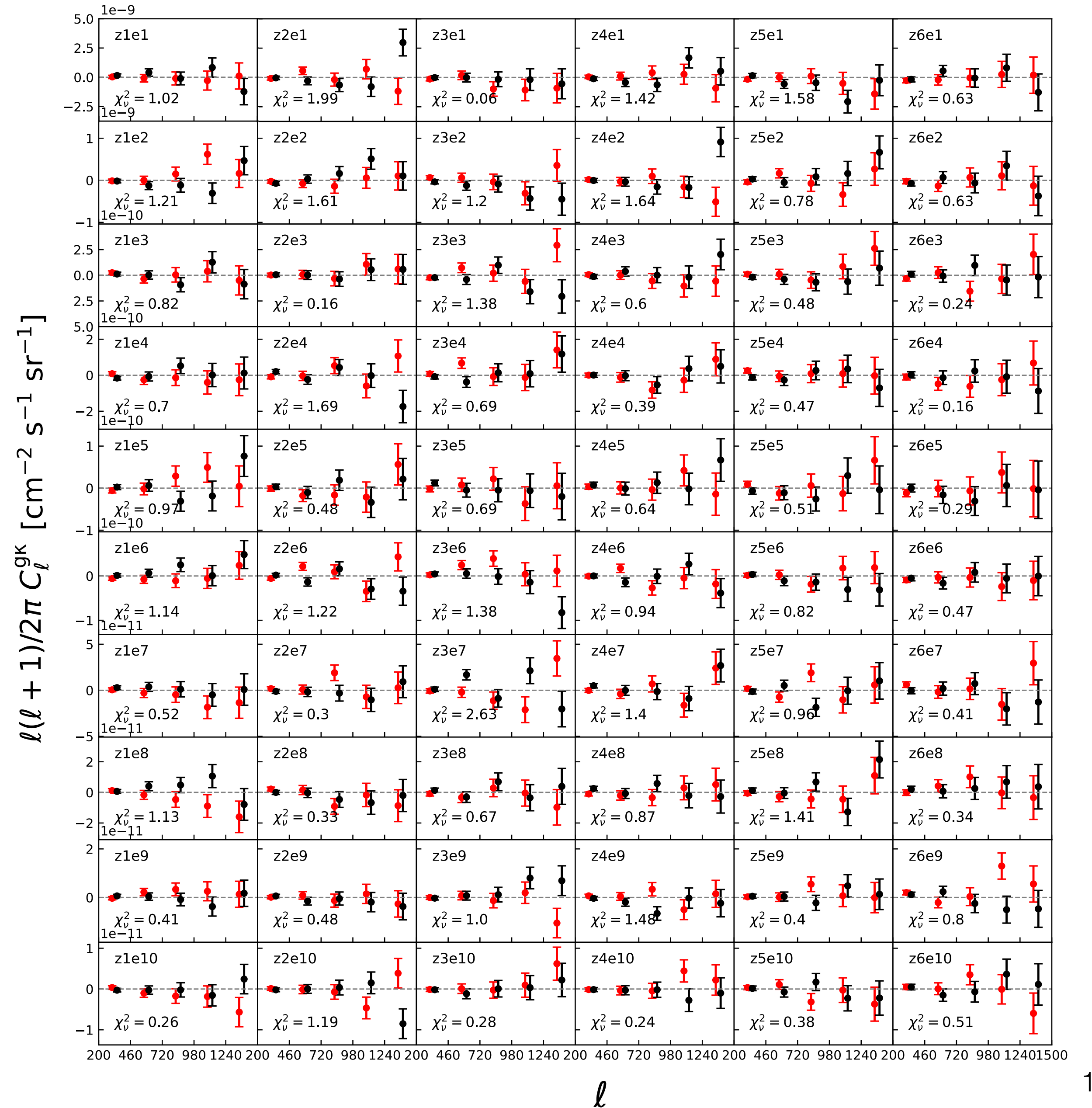
- Six tomographic bins (weak lensing)
- Ten energy bins (UGRB)
- **No significant signal detected**



Result: cross-correlation measurements

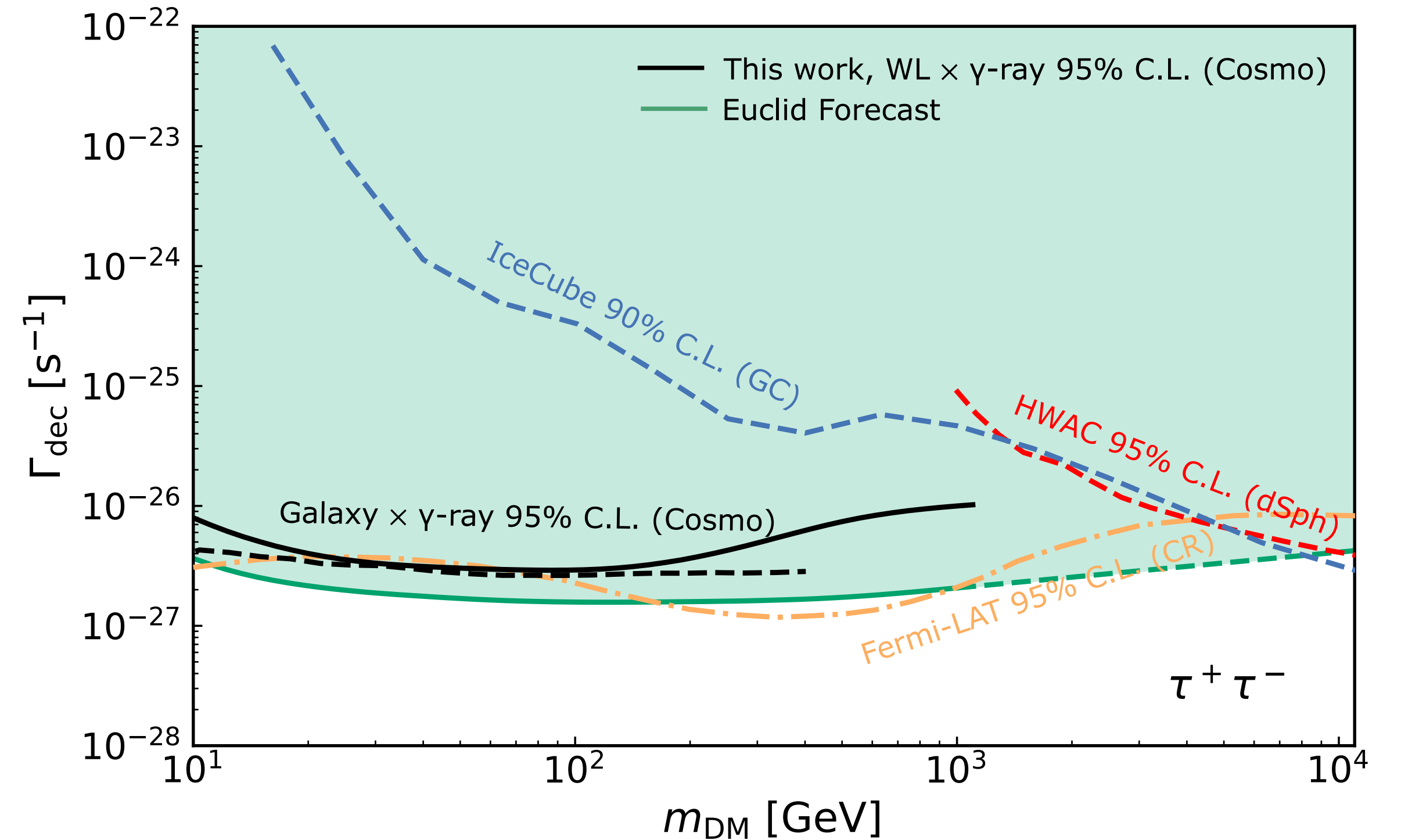
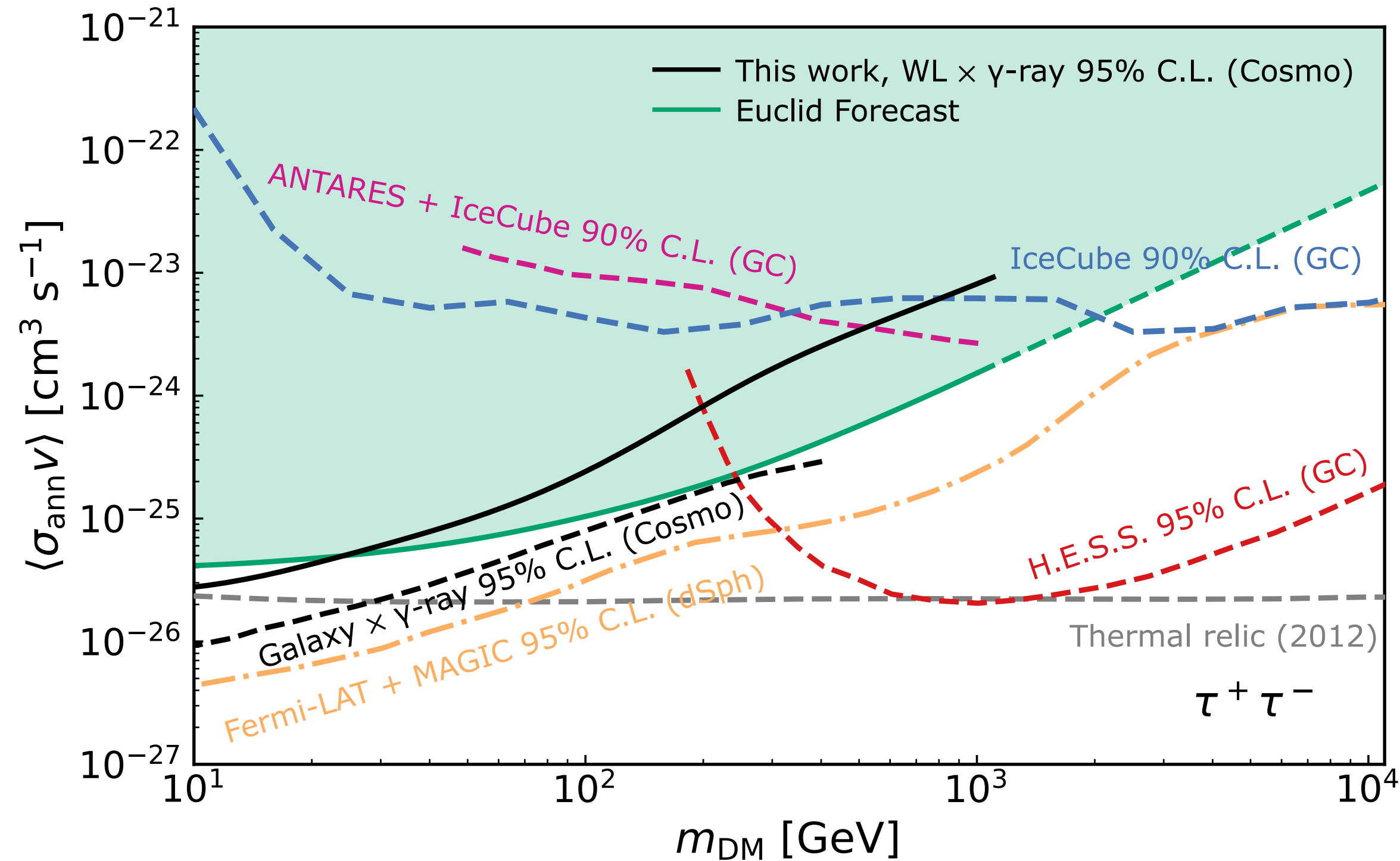
Black for E-mode
Red for B-mode

- Six tomographic bins (weak lensing)
- Ten energy bins (UGRB)
- No significant signal detected



Results: constraints on DM parameters

No significant signal → How large the DM contribution is allowed by the data? → 95% upper bounds



Upper bounds on the WIMP **annihilation cross-section** $\langle \sigma_{\text{ann}} v \rangle$ (left) & **decay rate** Γ_{dec} (right) for the $\tau^+ \tau^-$ state, compared to constraints from local probes.

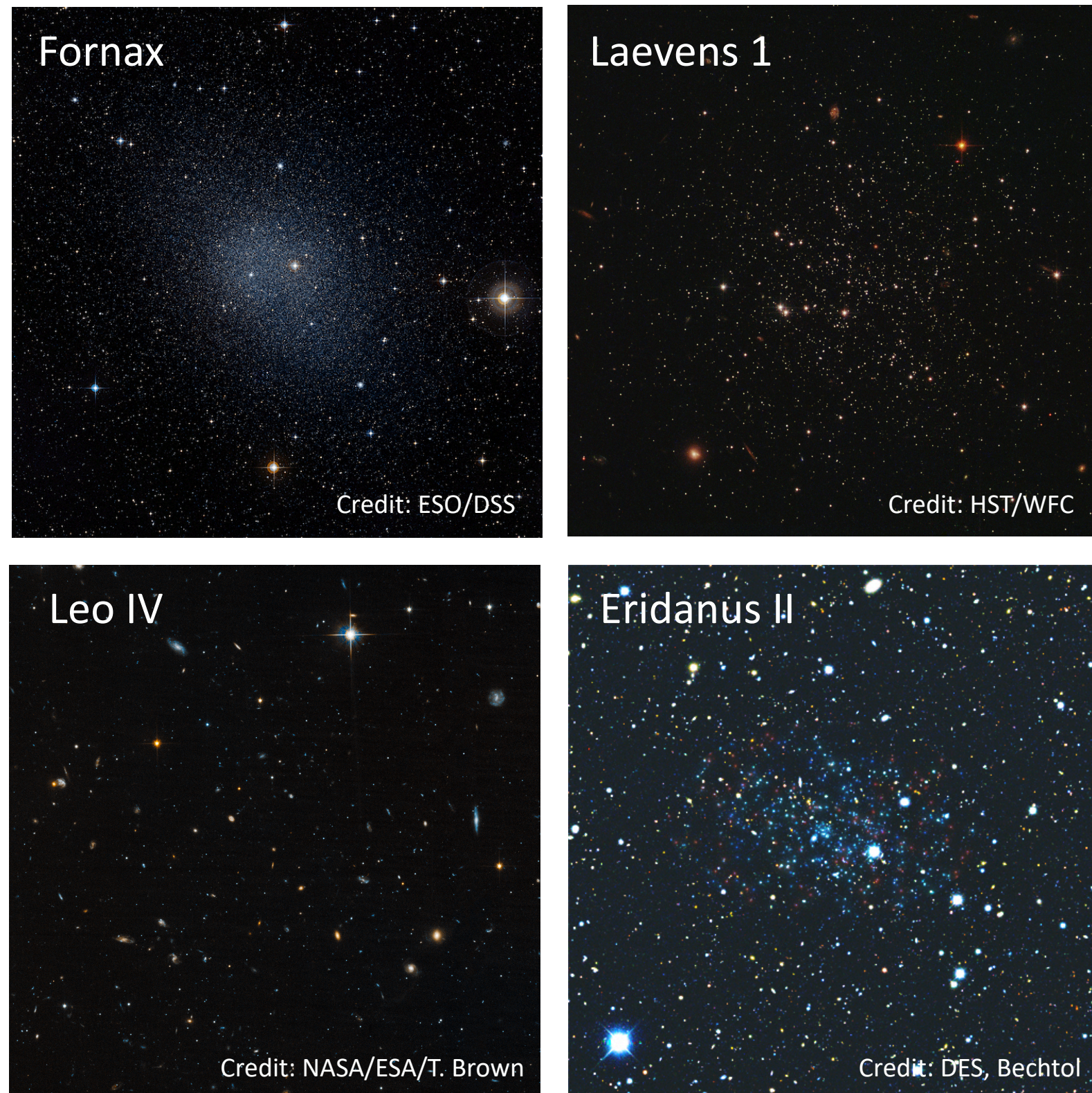
GC: Galactic centre; dSph: dwarf spheroidal galaxies; Cosmo: cosmological probe.

The forecast uncertainty is reduced by roughly a factor of $\sim 2-4$ compared with the current KiDS case.

Local substructure: Ultra-Faint Dwarfs (UFDs)

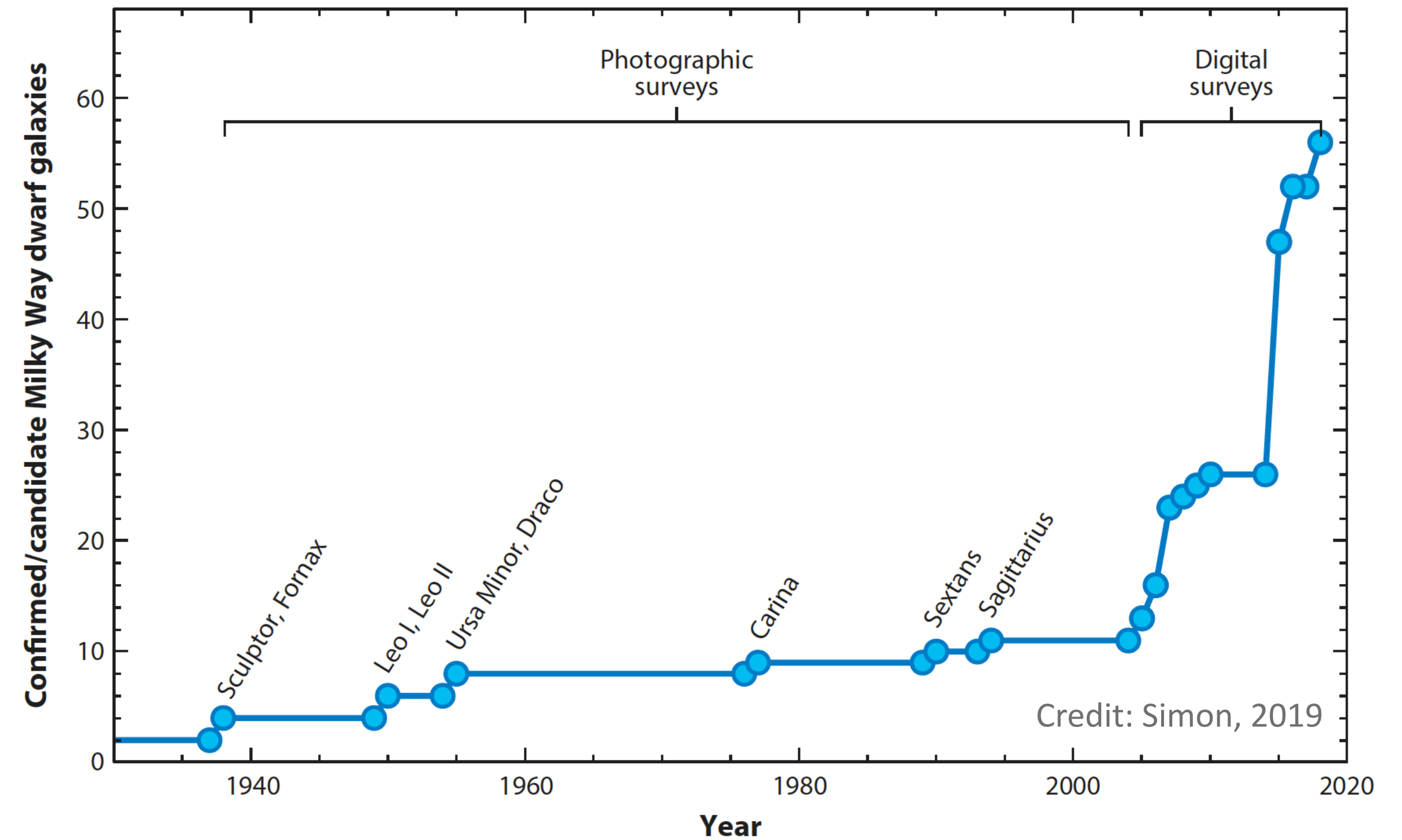
DM-dominated systems, but observationally incomplete

WHAT ARE UFDs?



- **DM-dominated** with highest known M/L ratios
- **Cleanest targets for indirect DM searching**, old and metal-poor
- **Local tests** of Λ CDM substructure predictions

WHY IS THE CENSUS INCOMPLETE?



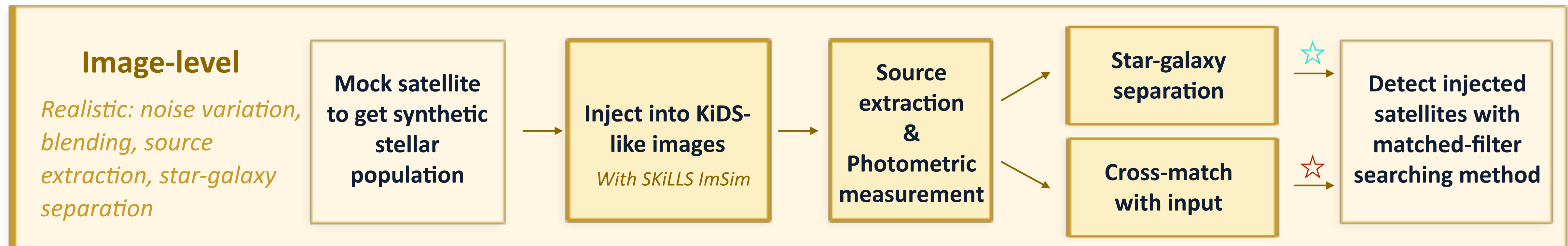
The observed population is selection-limited

Faint, diffuse, or distant systems are difficult to be found — the census is far from complete!

Observational selection function

UFDs selection function: image-level injection-recovery simulations

Testing what KiDS could actually detect - as a case study



~20,000
mock satellites injected

Sample mock satellites with parameters:

M_s - stellar mass (M_V)

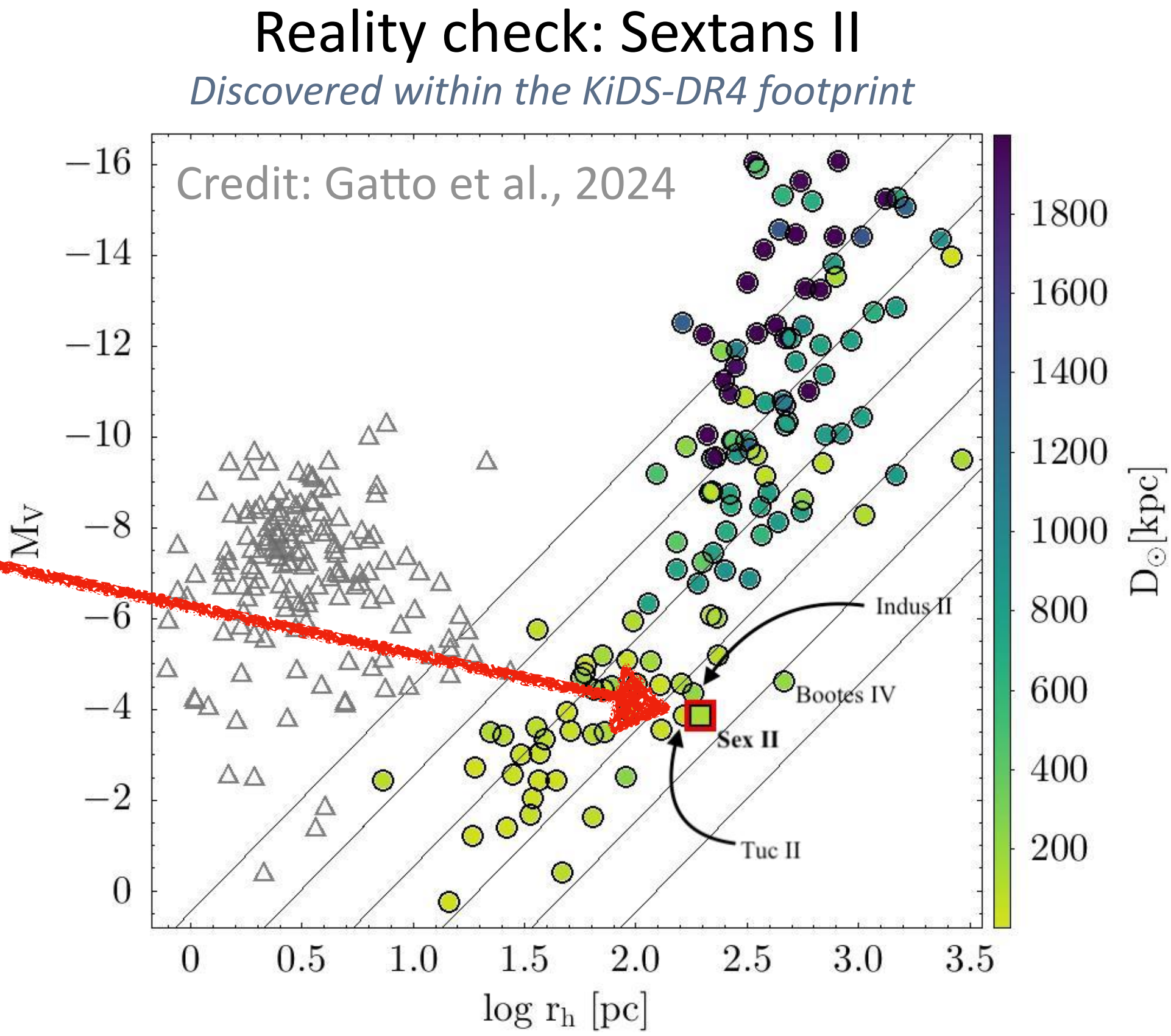
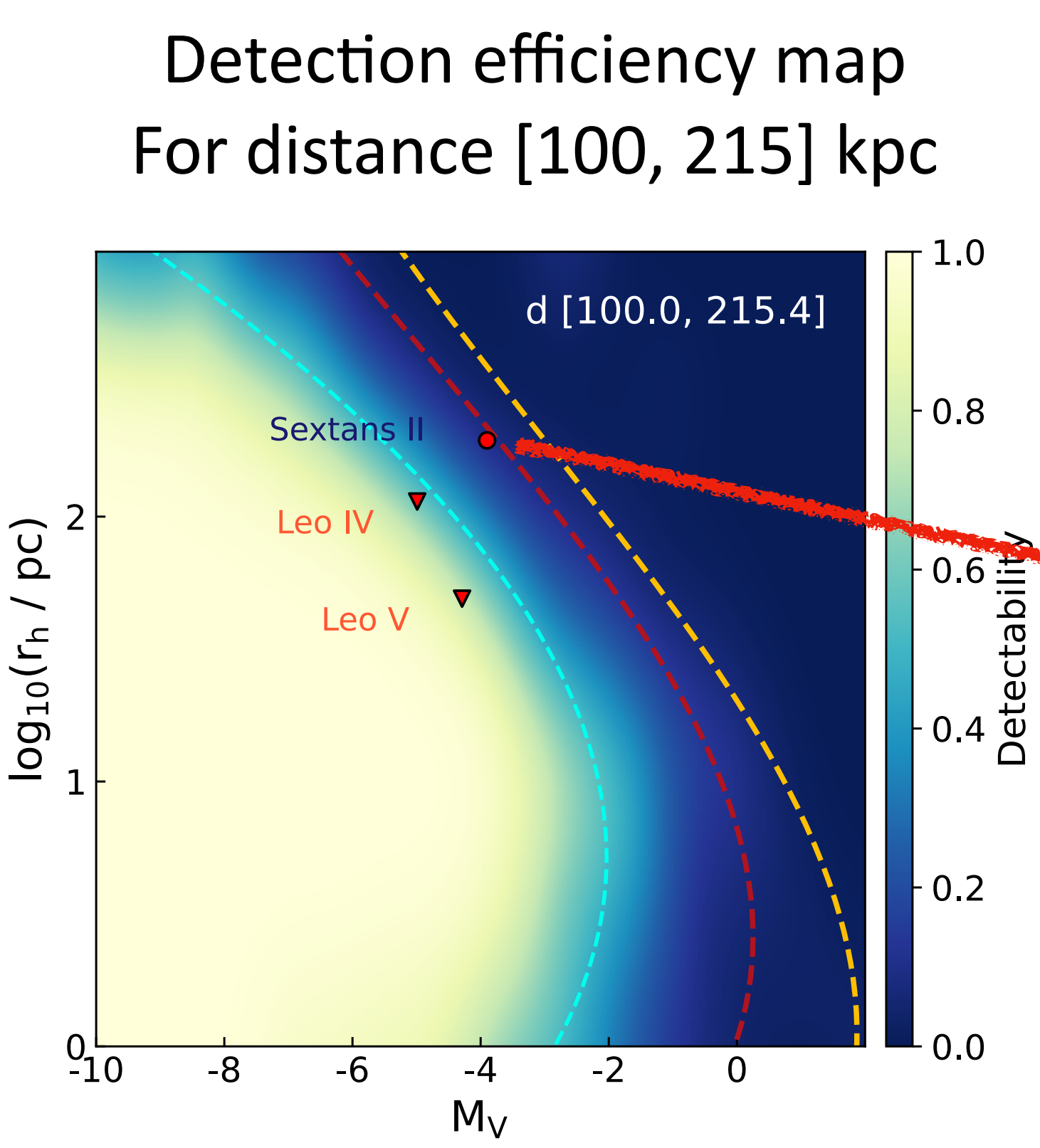
r_h - half-light radius

d - heliocentric distance

Detectability: **Recovery fraction** in each parameter bin
→ KiDS image-level selection function $P_{\text{det}}(M_V, r_h, d)$

Local substructure: UFDs detection efficiency & selection function

A realistic selection function is essential for interpreting the satellite census and indirect-search target samples.

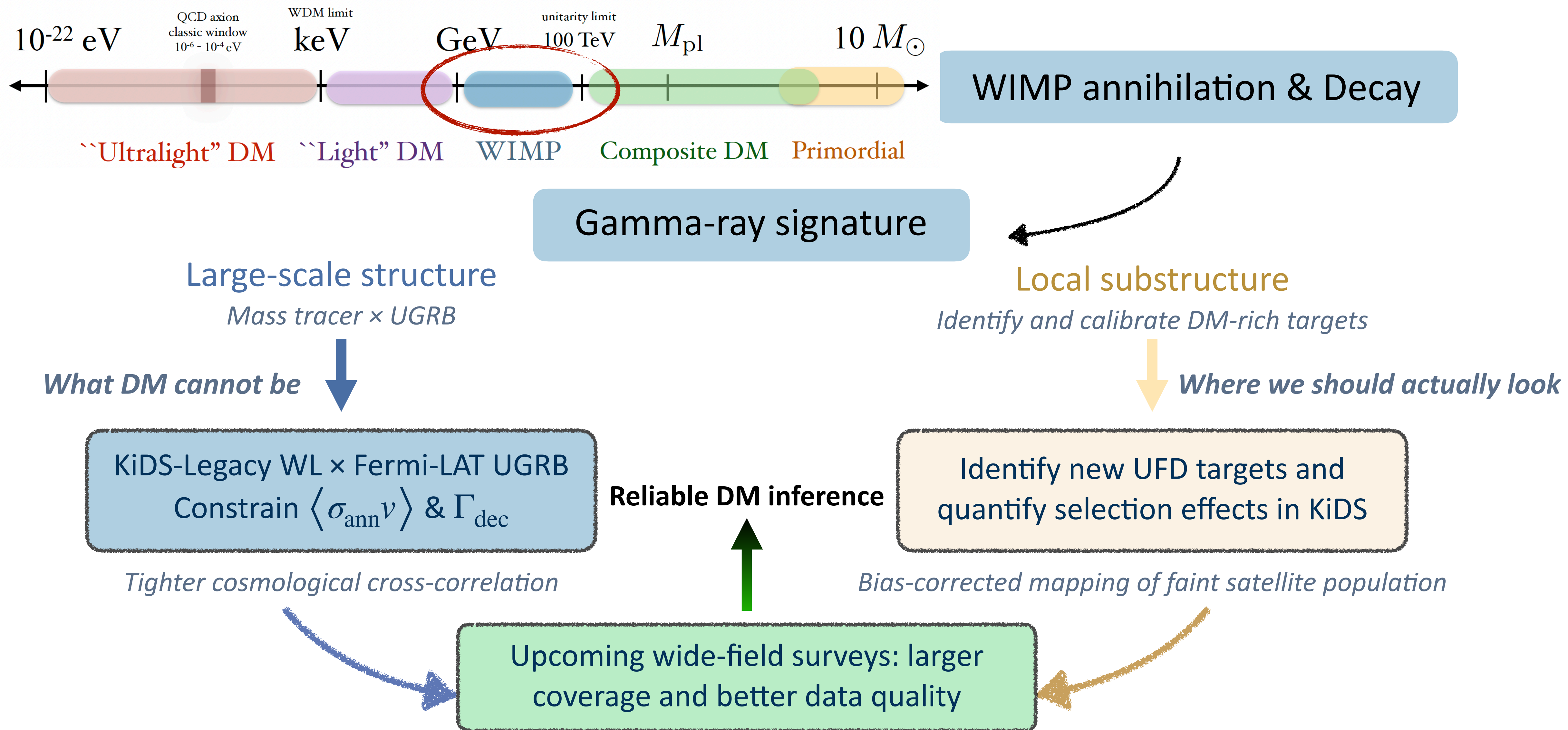


Simulation type

- Catalogue-level
- Image-level, ideal star selection
- Image-level, realistic SG separation

Catalogue-level	71.3%
Image-level, ideal stars	48.7%
Image-level, realistic SG	10.8%

Bridging scales for DM searches and outlook



Conclusion

RESULT 01

Cosmological scale

KiDS-Legacy × Fermi-LAT

- No significant UGRB × WL signal was detected
- Upper limits on WIMP annihilation and decay
- Euclid-like forecast: 2-4× tighter constraints

Complementary to local target-based constraints.

RESULT 02

Local scale

KiDS UFDs detection efficiency

- Catalogue case matches the results from previous study;
- Image case shows an overall lower detection efficiency for small satellites at distances > 100 kpc

Important for satellite census for indirect DM searches

OUTLOOK

Future

Better data, better modelling, better simulations

Future searches will benefit from:

- **Larger and deeper surveys**
- **Improved foreground and systematics modelling**
- **More realistic image-level simulations**

Stage-IV surveys

systematics

real-tile injection

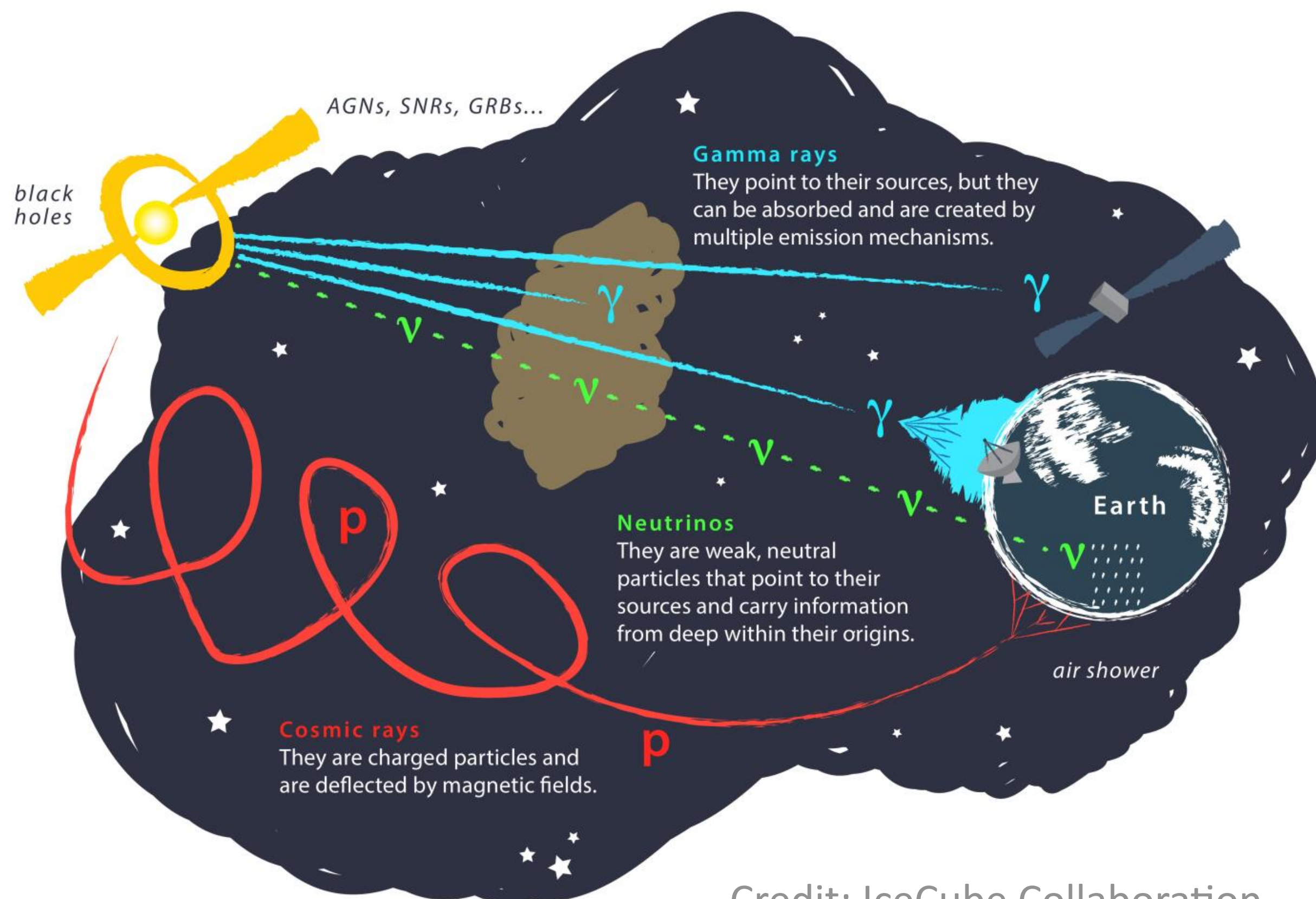
alternative DM
candidates

*Method improvements can extend beyond
WIMPs to broader DM scenarios*

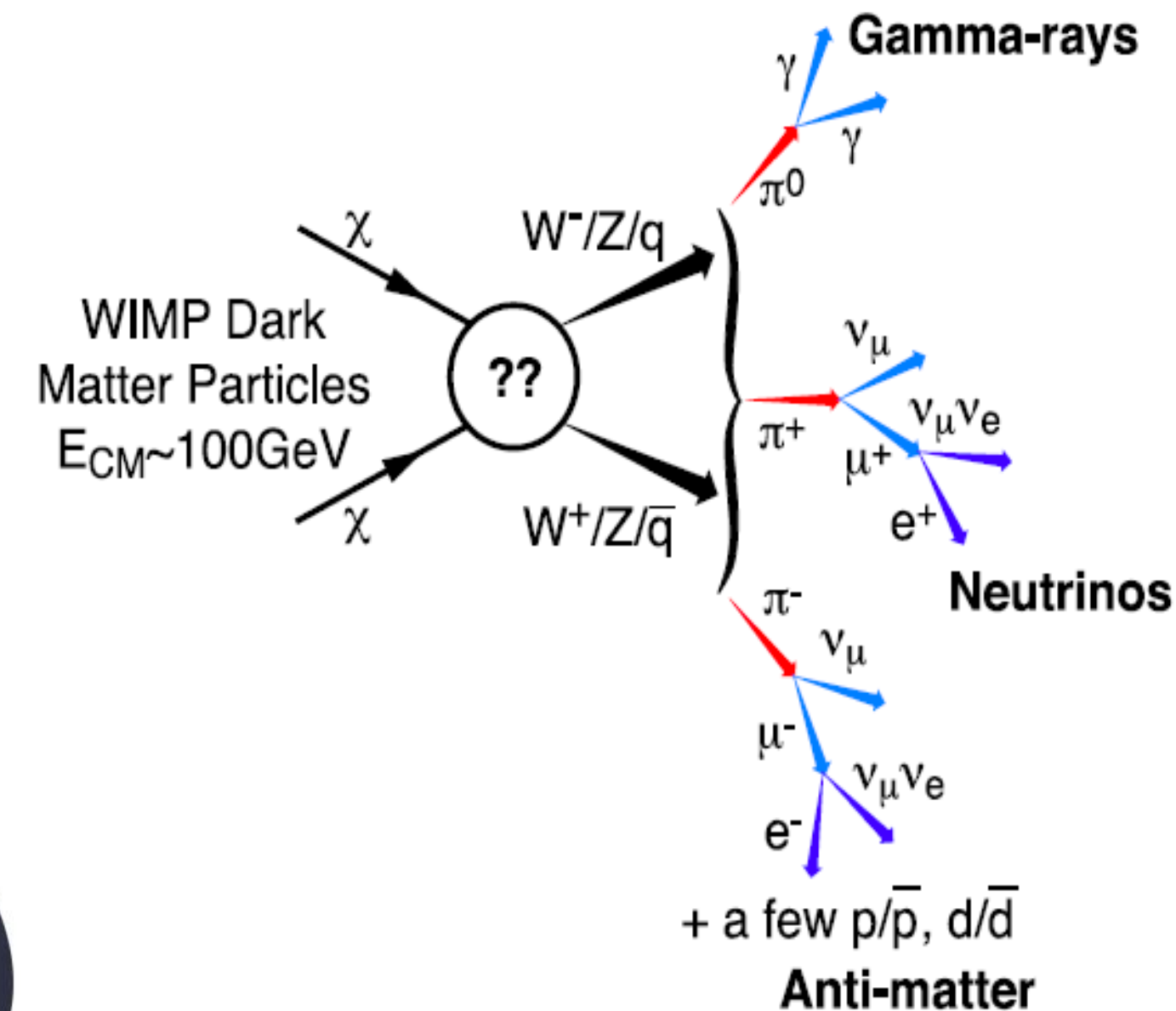
Backup

Theoretical frameworks: WIMPs interactions & indirect searching

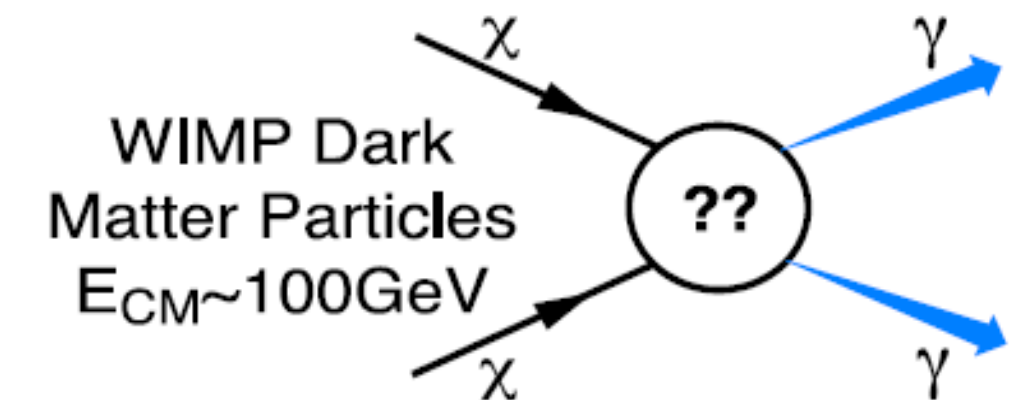
Indirect searches look for Standard Model particles produced by DM annihilation or decay.



Credit: IceCube Collaboration



Credit: Baltz et al. 2008



Continuous spectra

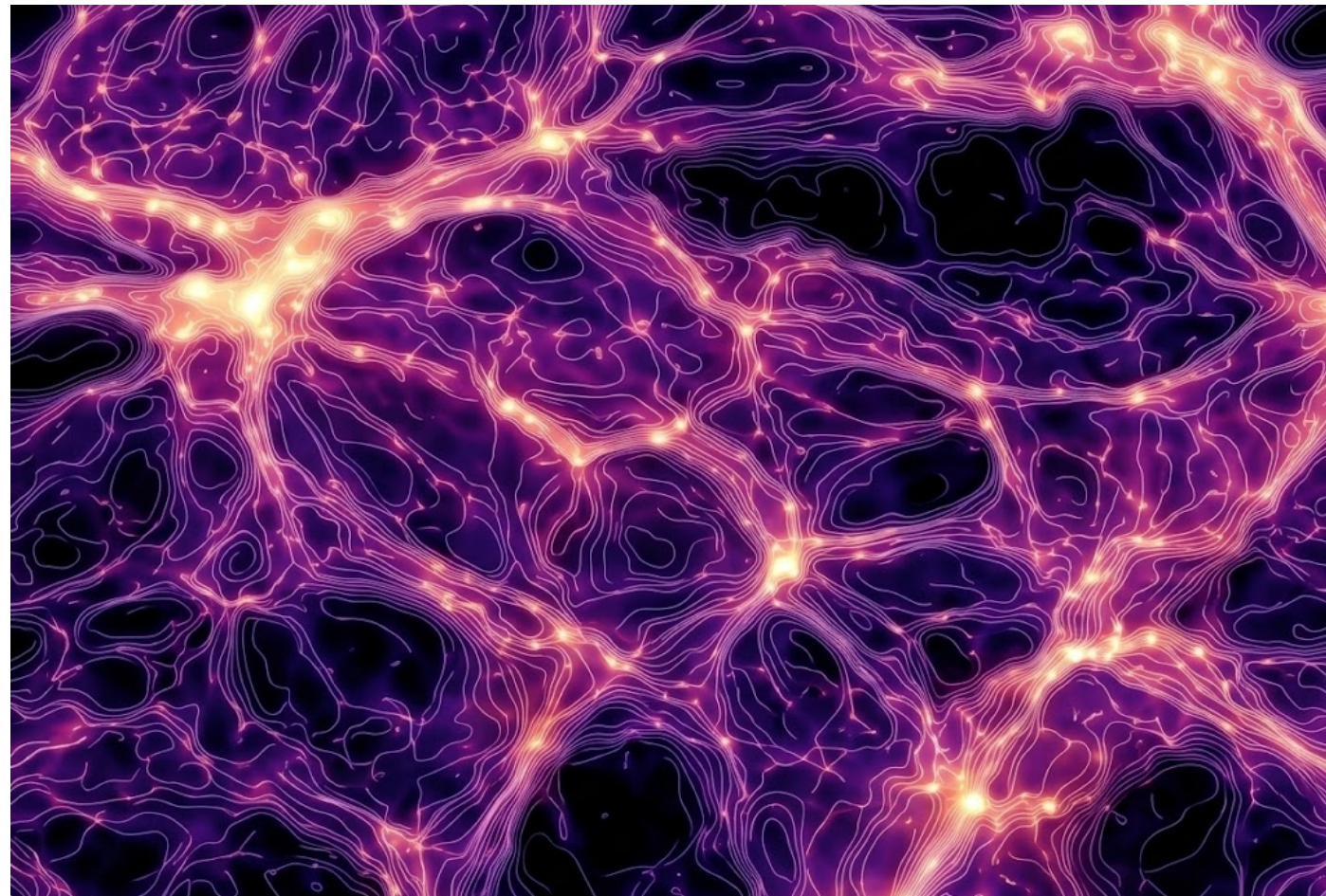
monochromatic line

- **Annihilation:** annihilation cross-section
 $\langle \sigma_{\text{ann}} v \rangle \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$
- **Decay:** decay rate (lifetime)
 $\Gamma \sim 10^{-28} - 10^{-26} \text{ s}^{-1}$

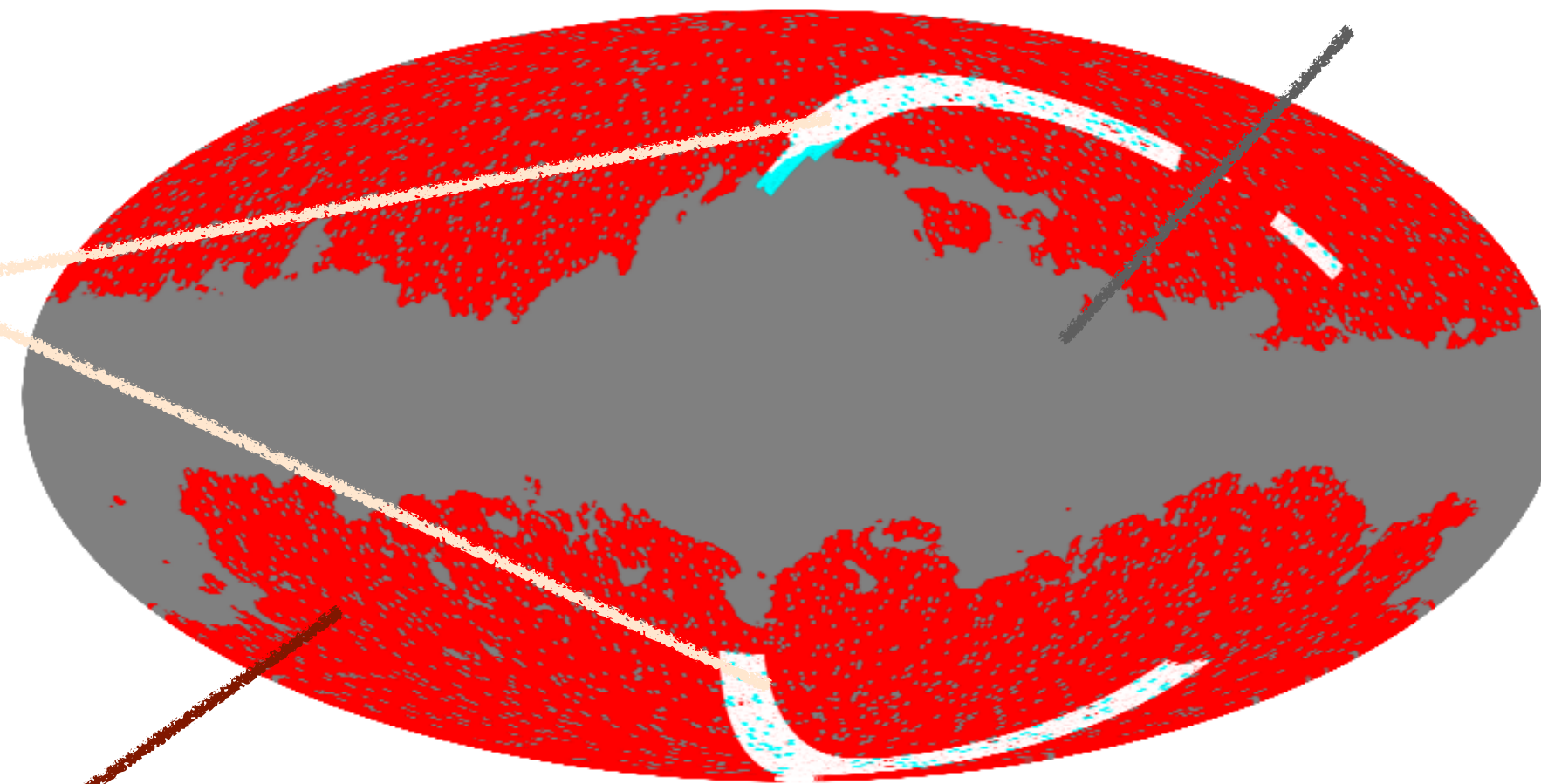
Large-scale DM searches: weak lensing × gamma rays

If DM contributes to the gamma-ray background, its signal should be statistically correlated with the mass distribution

Weak-lensing map



Foreground
diffusion mask



Statistical inference

Measured C_ℓ (UGRB × WL)
Two-point angular cross-power spectrum from data



Model prediction
DM annihilation / decay + astrophysical backgrounds



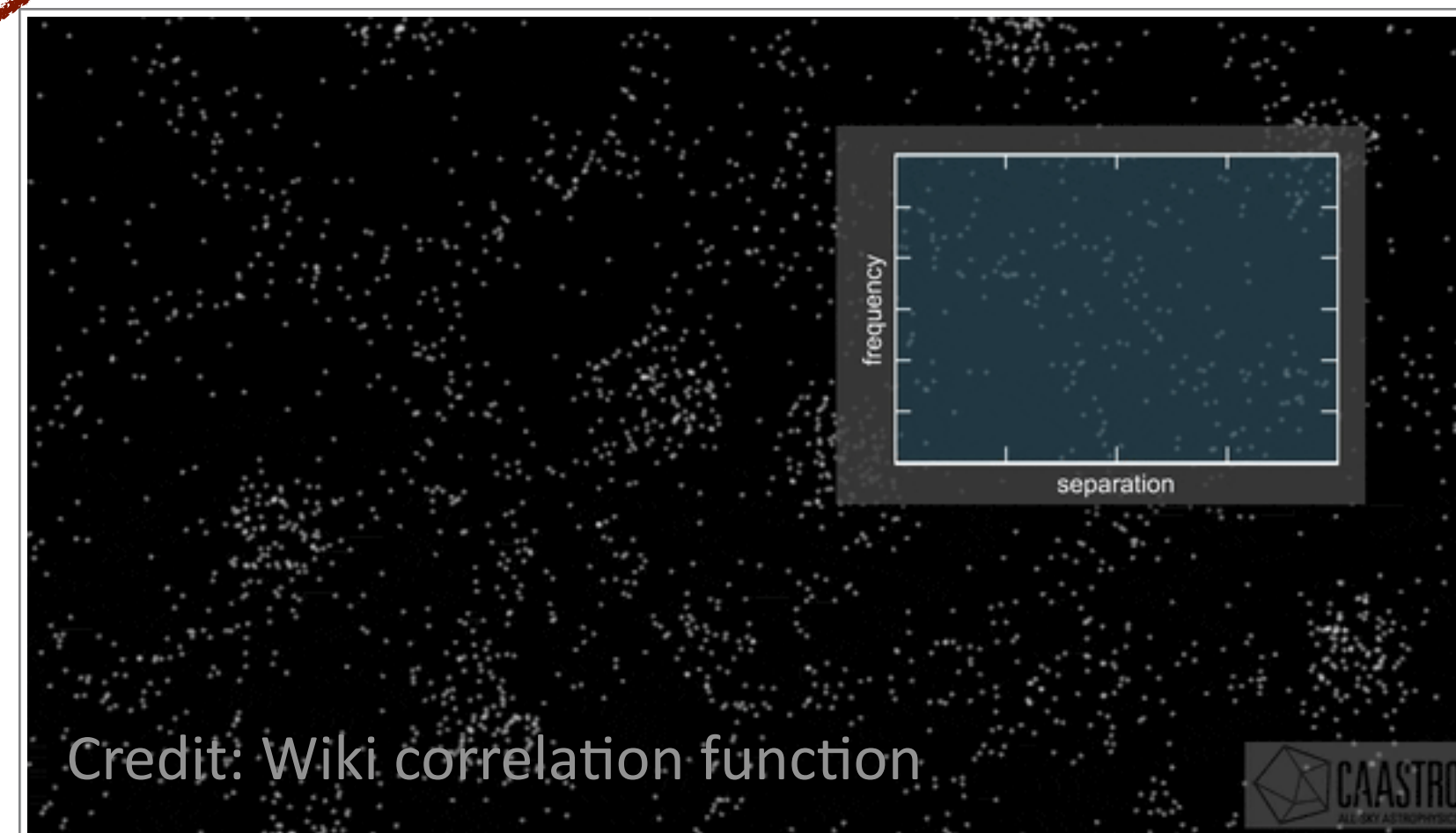
Likelihood fit
Vary the DM parameter and find the model most consistent with the measured C_ℓ



DM constraints
upper limits on $\langle \sigma_{\text{ann}} v \rangle$ or Γ_{dec}



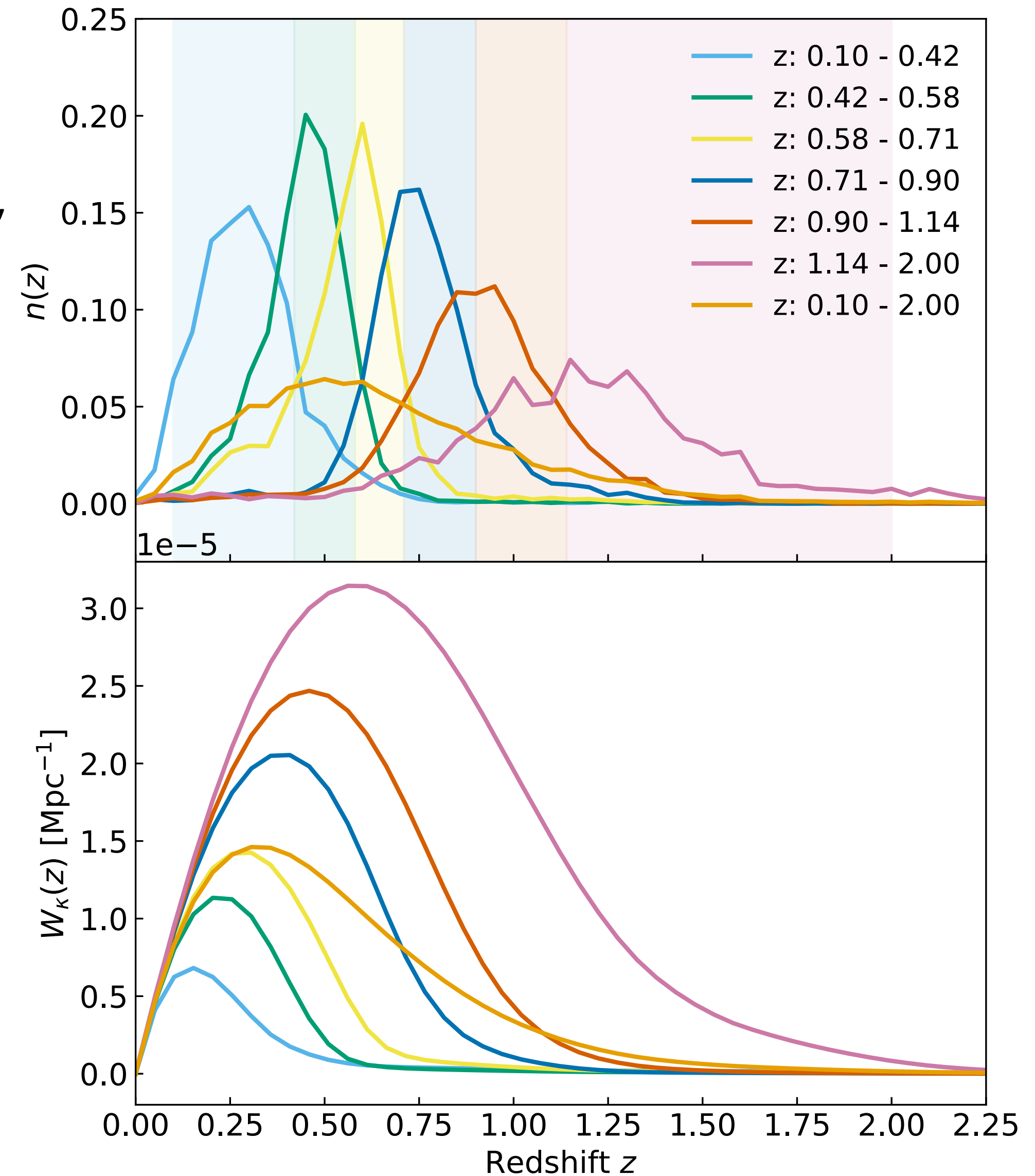
UGRB



Two-point correlation

Model: Weak lensing tracer

$$W_k(z) = \underbrace{\frac{3H_0^2\Omega_M}{2}(1+z)}_{\text{Level of gravitational potential caused by matter overdensity}} \chi(z) \overset{\text{Lens to observer}}{\uparrow} \int_z^\infty dz' \frac{\chi(z') - \chi(z)}{\chi(z')} \underbrace{n(z')}_{\text{Source galaxy distribution}} \downarrow \text{Lensing geometry: giving a lens at } z, \text{ how many sources can be lensed by it}$$



Model: DM annihilation & decay

$$\Delta^2(z) = \frac{\langle \rho_{\text{DM}}^2 \rangle}{\bar{\rho}_{\text{DM}}^2} = \int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn}{dM}(M, z) [1 + b_{\text{sub}}(M, z)] \times \int d^3\mathbf{x} \frac{\rho^2(\mathbf{x} | M, z)}{\bar{\rho}_{\text{DM}}^2}$$

- Annihilation:

$$W_{g_{\text{ann}}}(z, E) = \frac{(\Omega_{\text{DM}} \rho_c)^2}{4\pi} \frac{\langle \sigma_{\text{ann}} v \rangle}{2m_{\text{DM}}^2} (1+z)^3 \Delta^2(z) \frac{dN_{\text{ann}}}{dE}[E(1+z)] e^{-\tau[z, E(1+z)]}$$

- Decay:

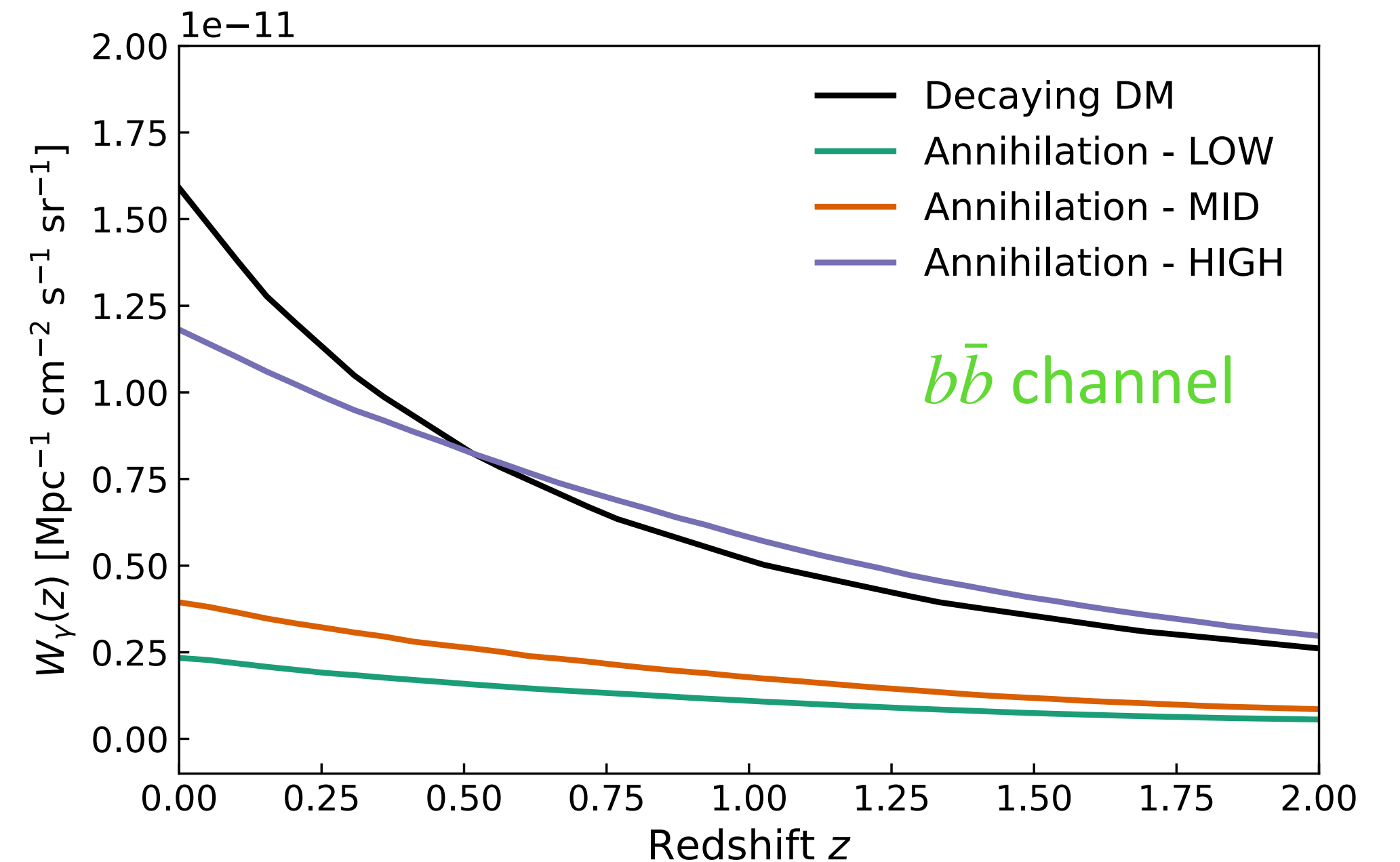
$$W_{g_{\text{dec}}}(z, E) = \frac{\Omega_{\text{DM}} \rho_c}{4\pi} \frac{\Gamma_{\text{dec}}}{m_{\text{DM}}} \frac{dN_{\text{dec}}}{dE}[E(1+z)] e^{-\tau[z, E(1+z)]}$$

- Astrophysical sources: $W_{g_s}(z, E) = \chi(z)^2 \langle f_s \rangle$

Model parameters

Clumping factor: high/mid/low

Energy spectrum: varies across three different channels: $\tau^+\tau^-$, $\mu^+\mu^-$, $b\bar{b}$



Result: cross-correlation measurements

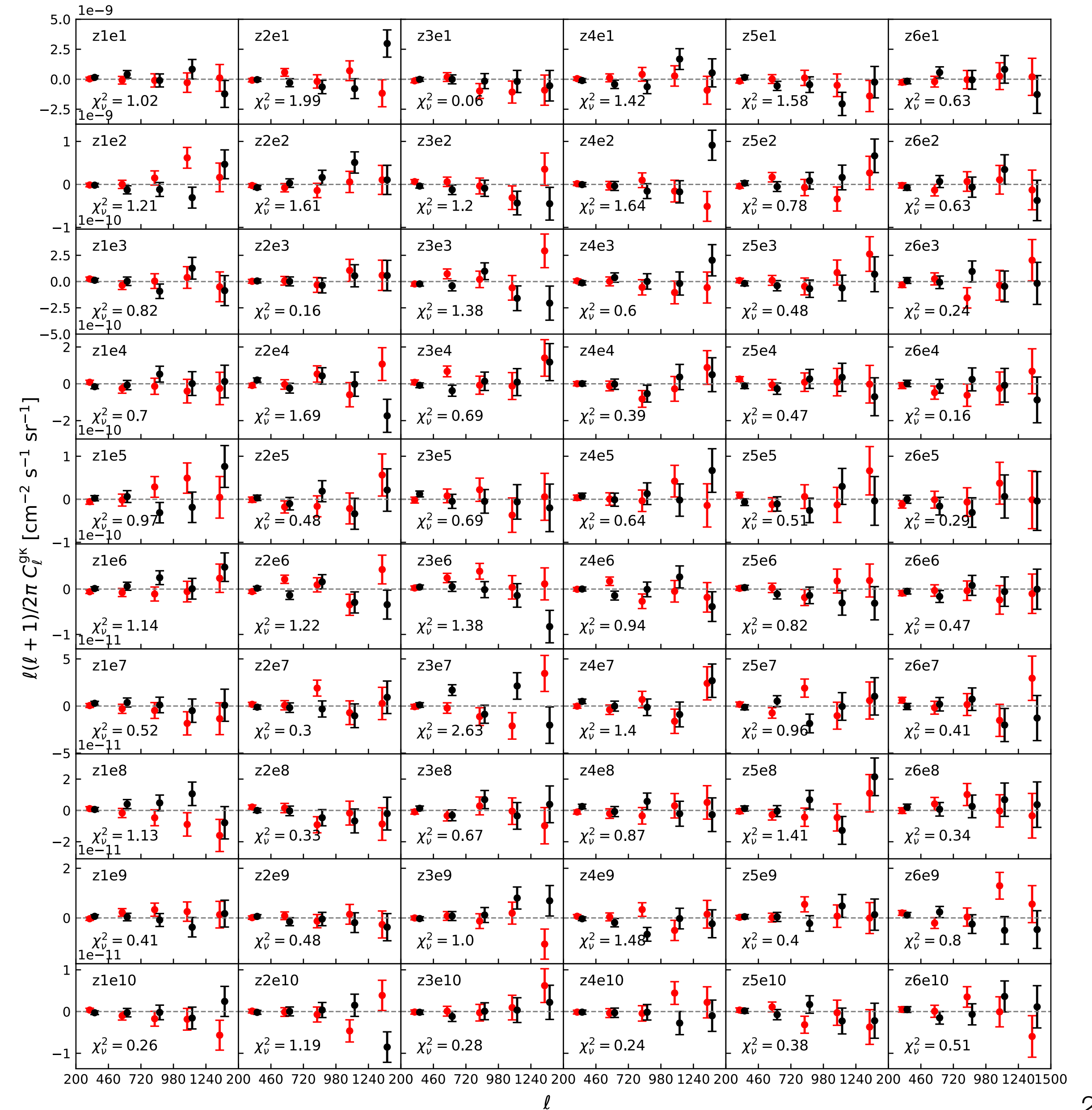
Black for E-mode

Red for B-mode

- Six tomographic bins (weak lensing)
- Ten energy bins (UGRB)

$$\chi_E^2 = 248.07 \quad \chi_B^2 = 256.28$$

- **No significant signal detected**

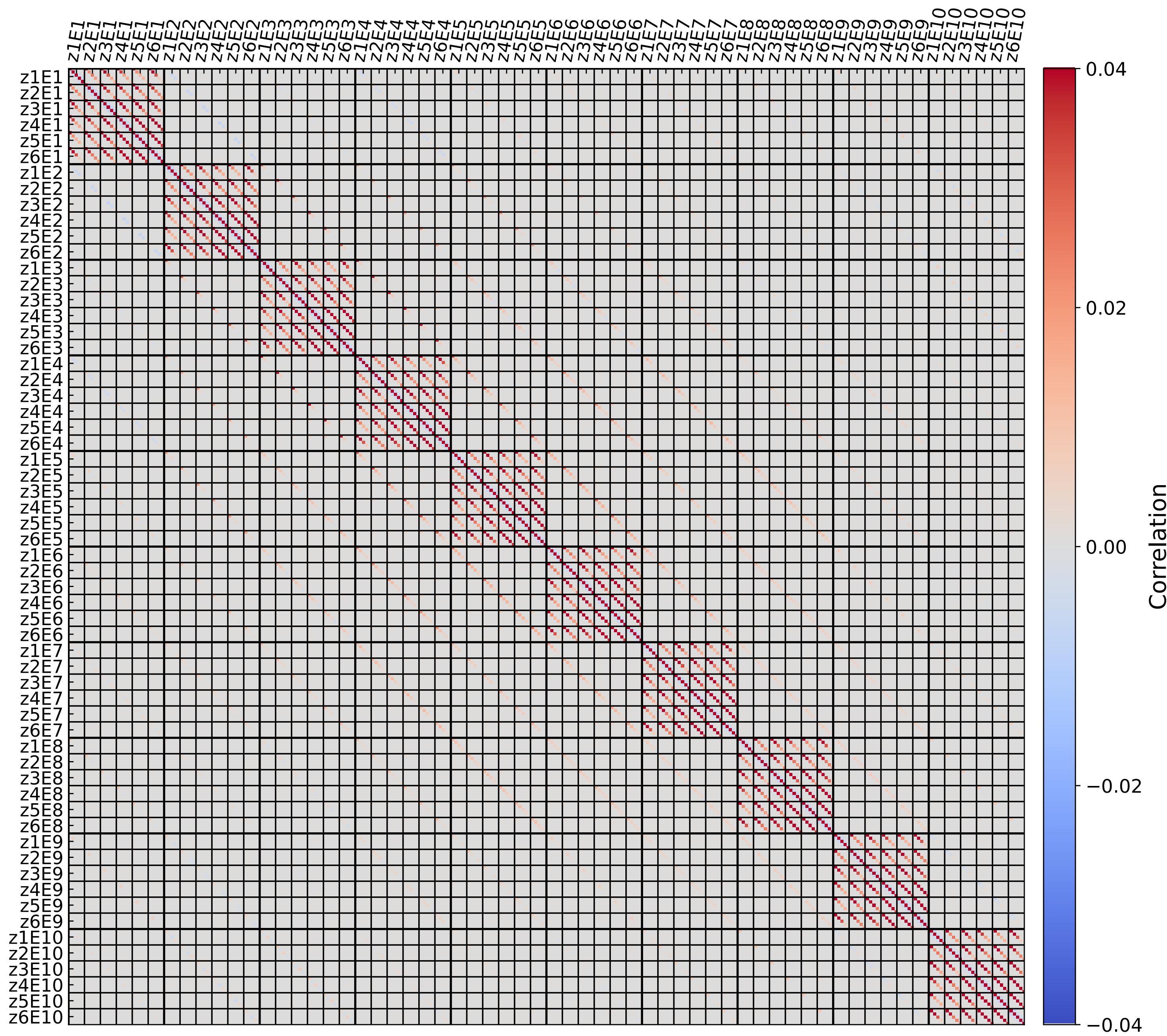


Covariance

Correlation matrix

From NaMaster Gaussian estimation

$$\text{Cov}\left[C_{\ell}^{g\kappa}\right] = \frac{1}{f_{\text{sky}}(2\ell + 1)\Delta_{\ell}} \left[\hat{C}_{\ell}^{gg}\hat{C}_{\ell}^{\kappa\kappa} + \left(\hat{C}_{\ell}^{g\kappa}\right)^2 \right]$$



Low χ^2 : inhomogeneous noise of the Fermi maps?

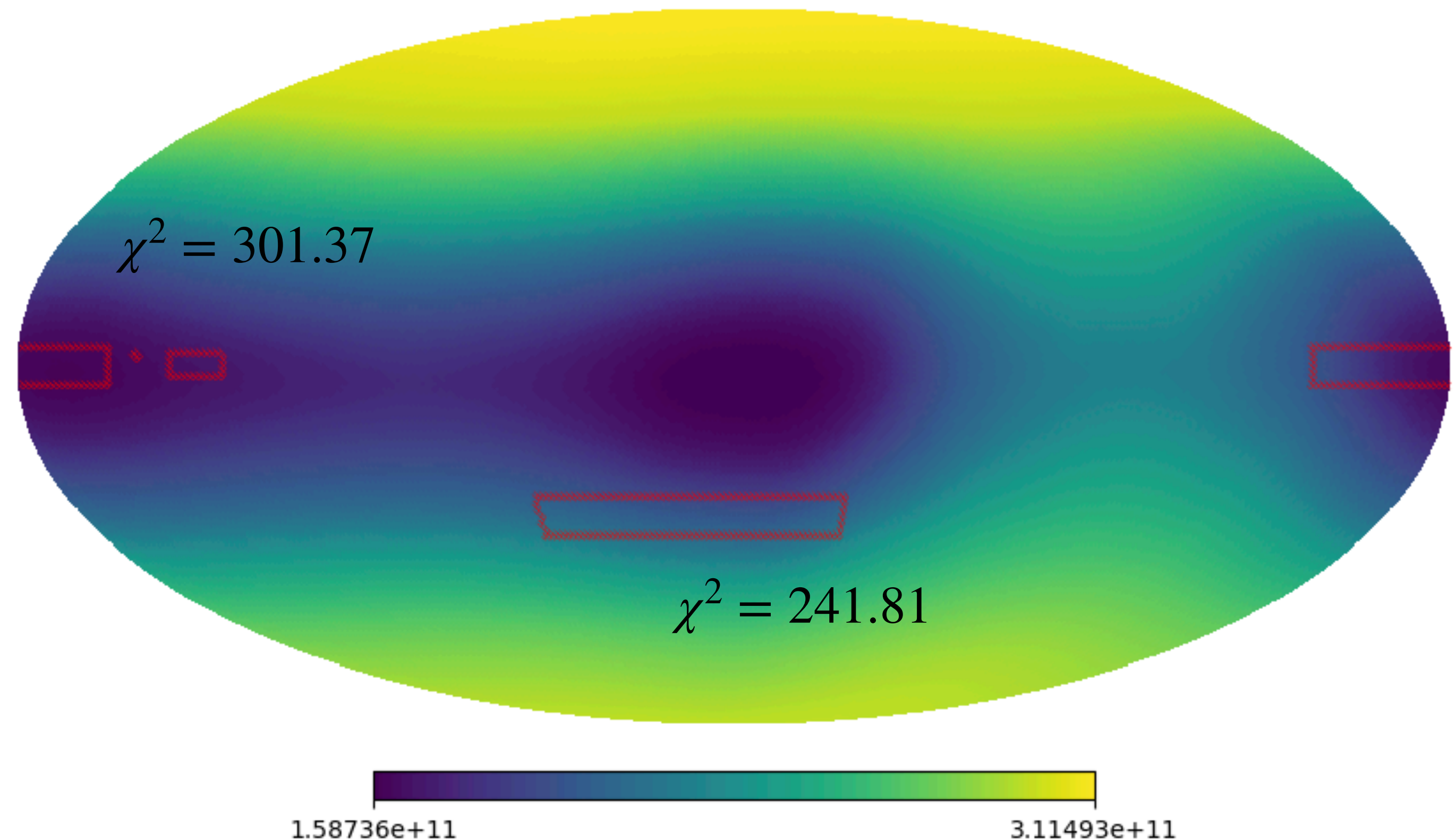
- **Fermi (Inhomogeneous)**

- Noise is dominated by Poisson with per-pixel variance following:

$$\text{Var}(I) \sim (\text{Signal} + \text{Backgrounds}) / \text{Exp}$$

- **KiDS (Homogeneous)**

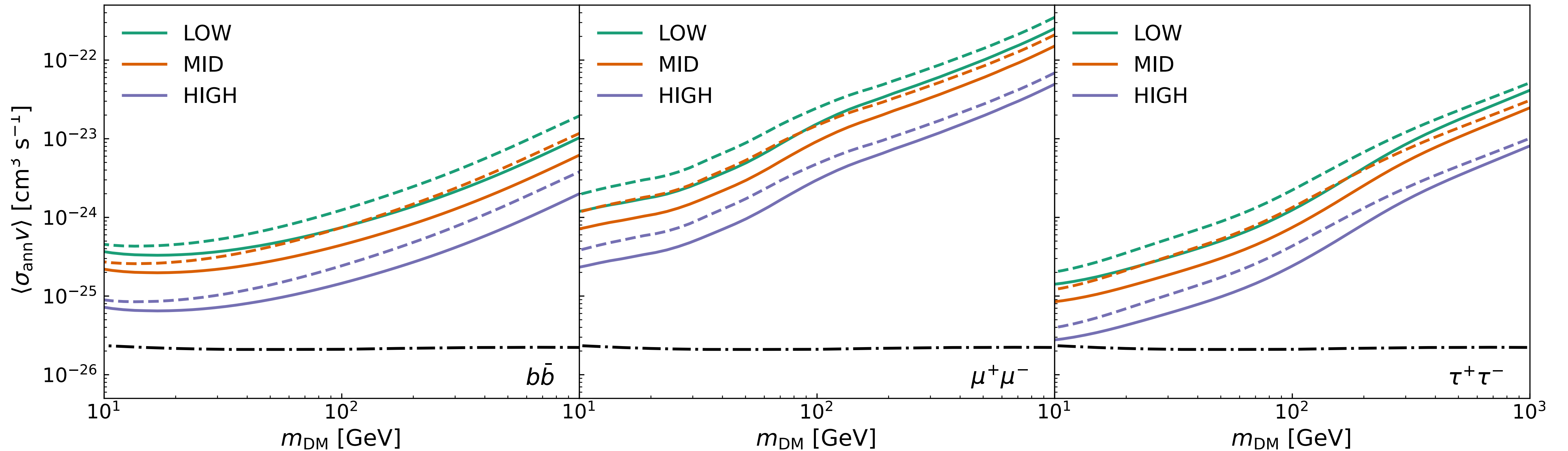
- Shape noise
- Gaussian covariance estimated from NaMaster assumes isotropic noise (when propagating the mode coupling)



Results: constraints on DM parameters

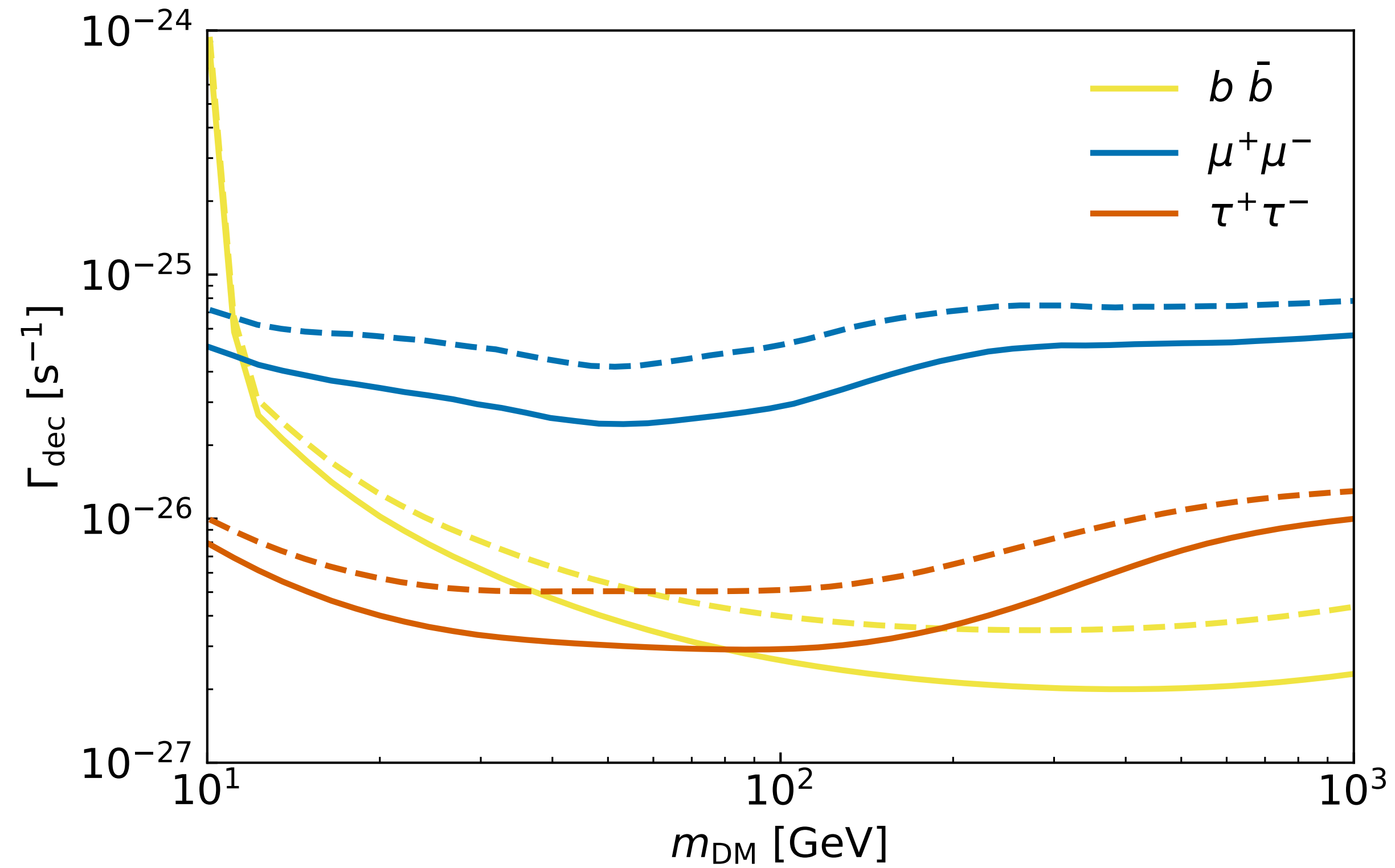
95% upper bounds for **thermally averaged annihilation cross-section** $\langle \sigma_{\text{ann}} v \rangle$

For DM clumping scenarios: **LOW**, **MID** and **HIGH**

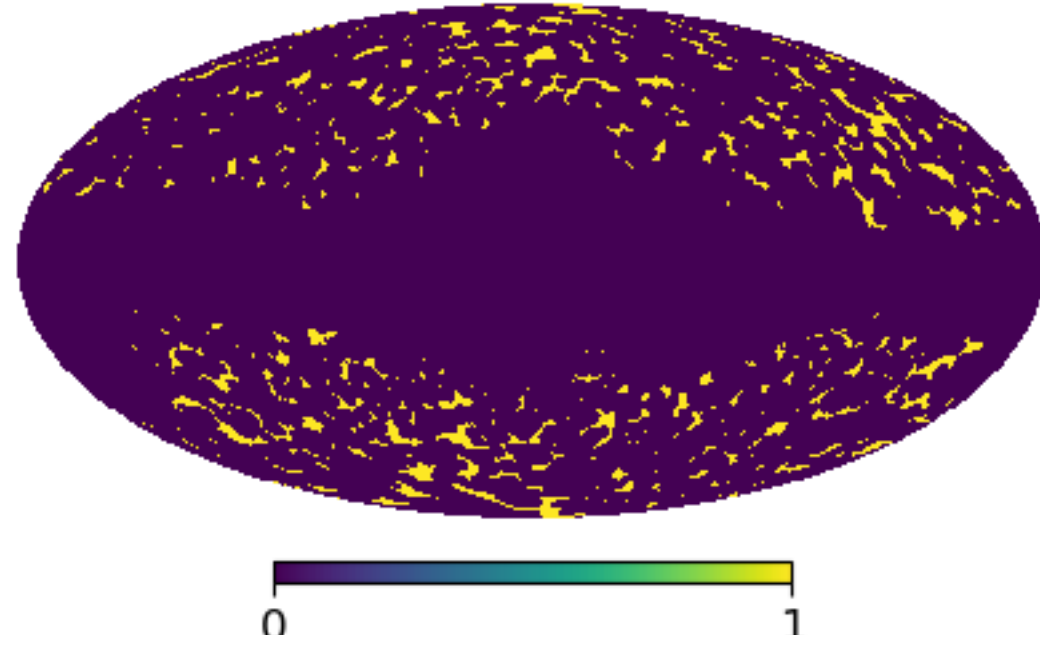


Results: constraints on DM parameters

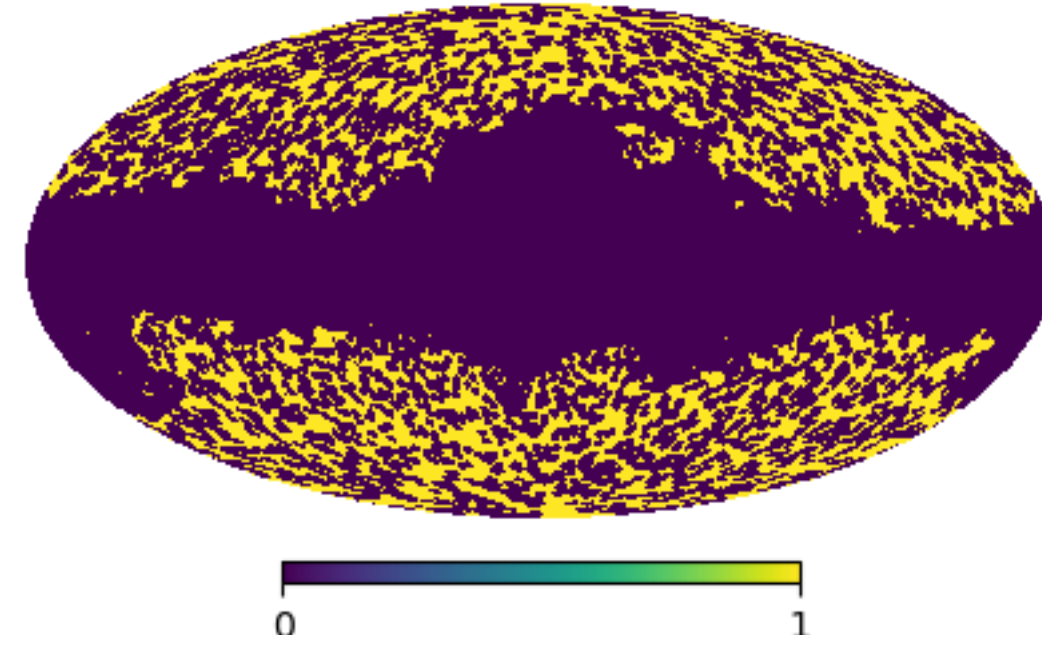
95% upper bounds for **decay rate** Γ_{dec}



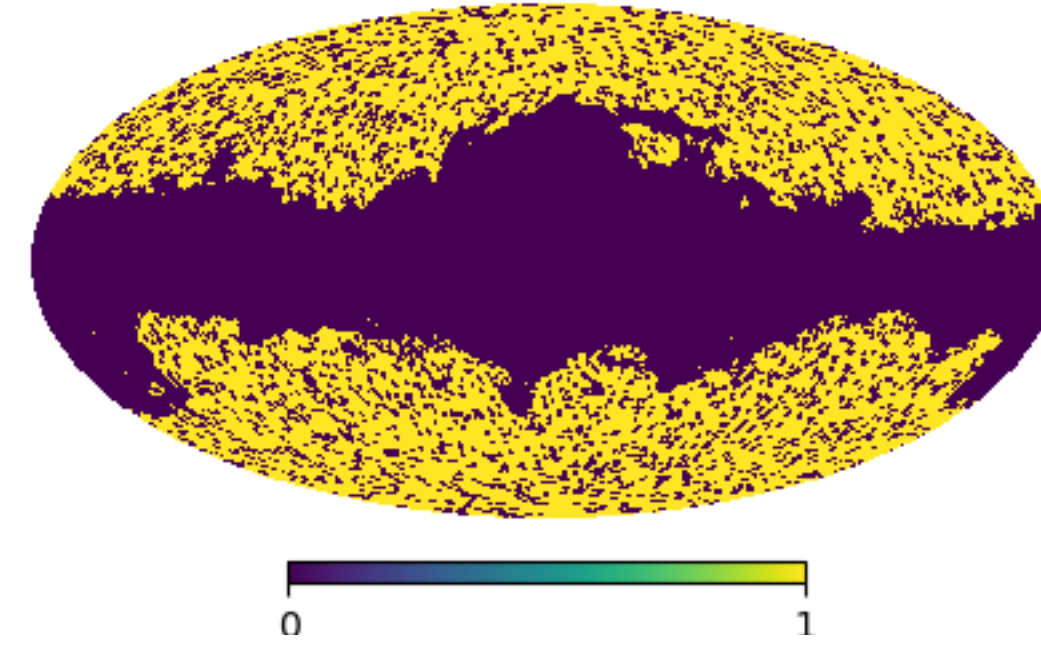
Macro Bin 0, Energy 5.25e+02 MeV



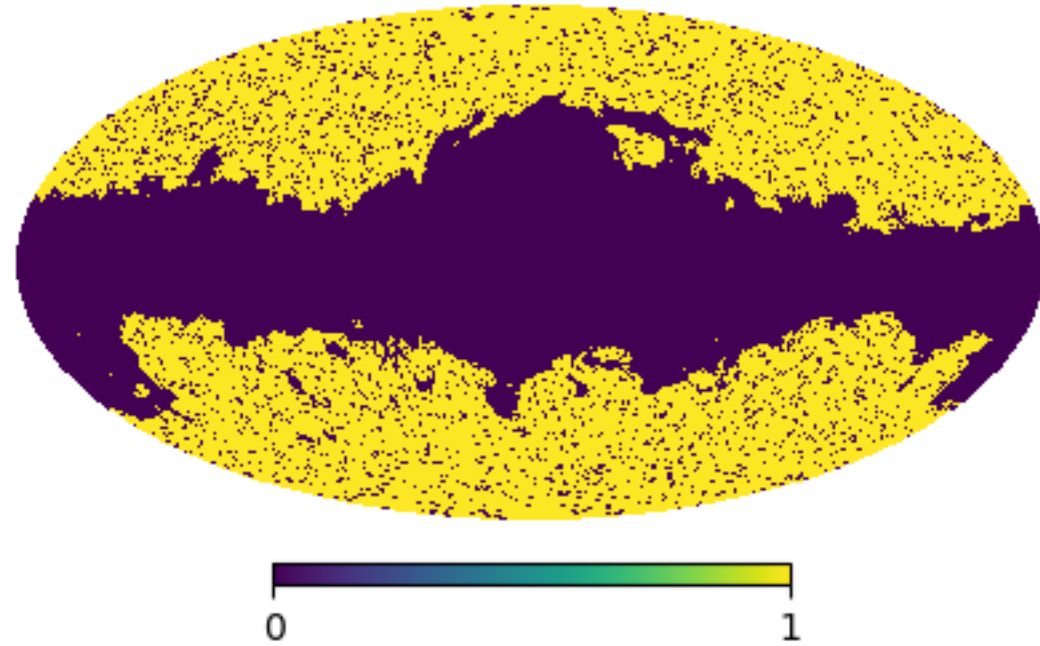
Macro Bin 1, Energy 1.00e+03 MeV



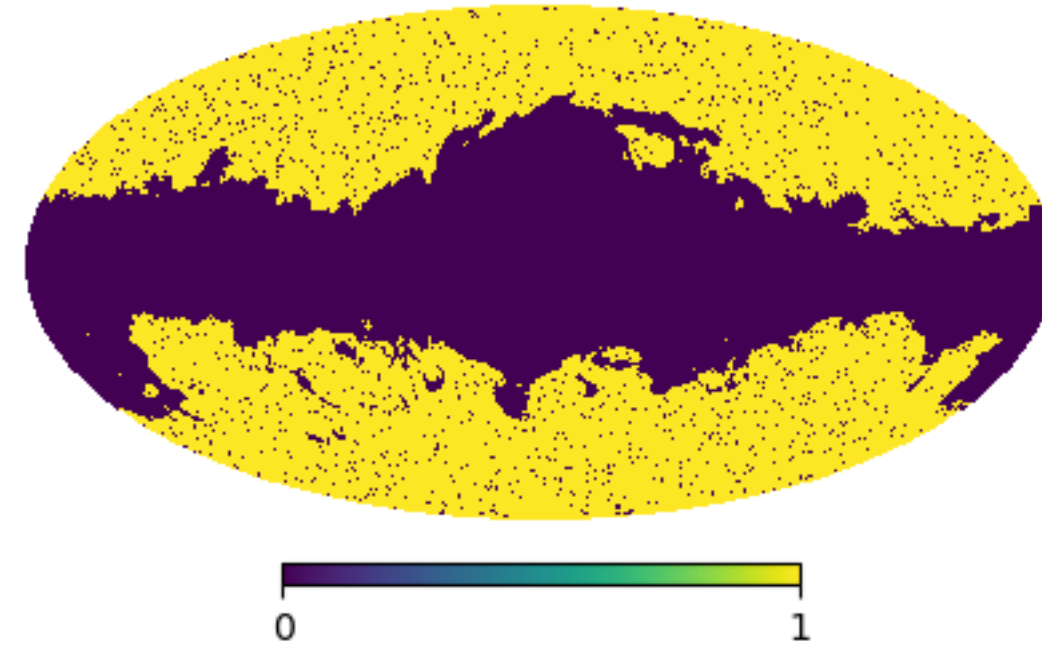
Macro Bin 2, Energy 2.09e+03 MeV



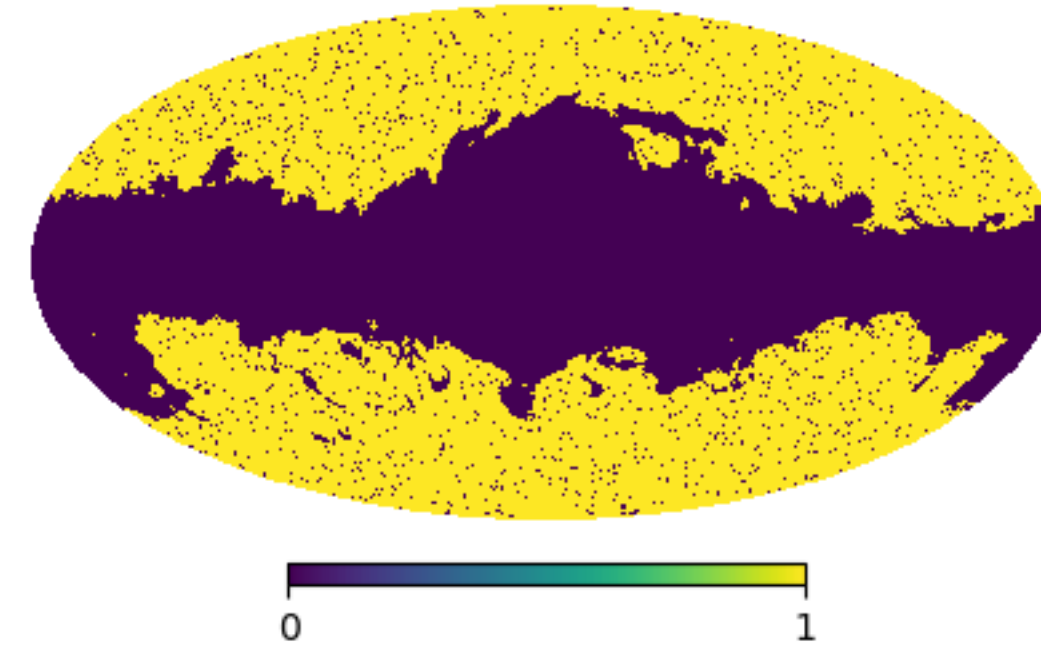
Macro Bin 3, Energy 3.98e+03 MeV



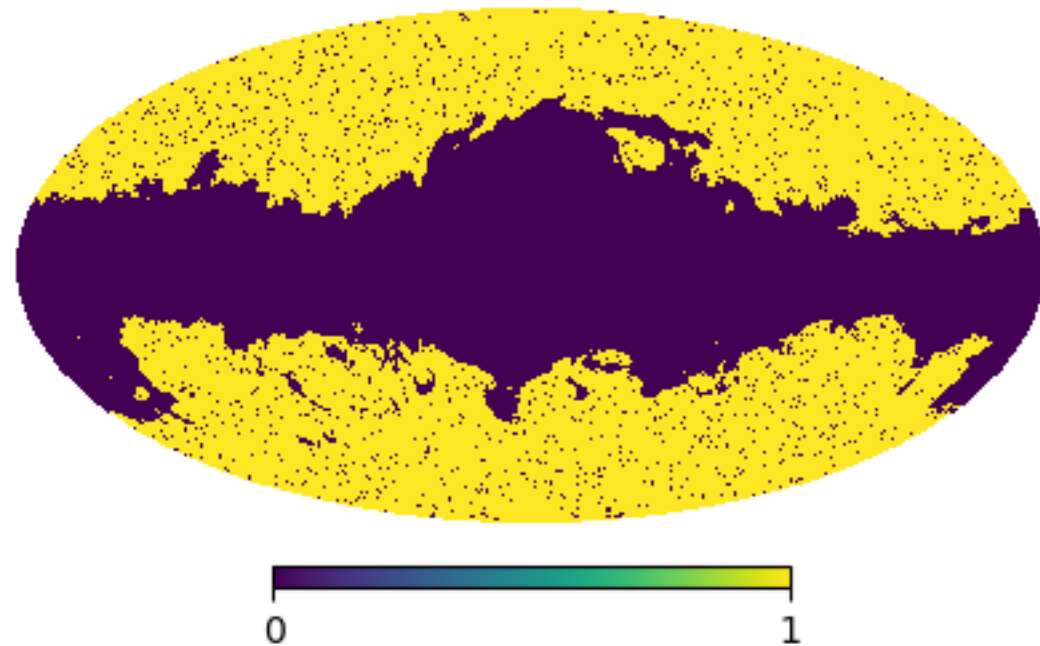
Macro Bin 4, Energy 8.32e+03 MeV



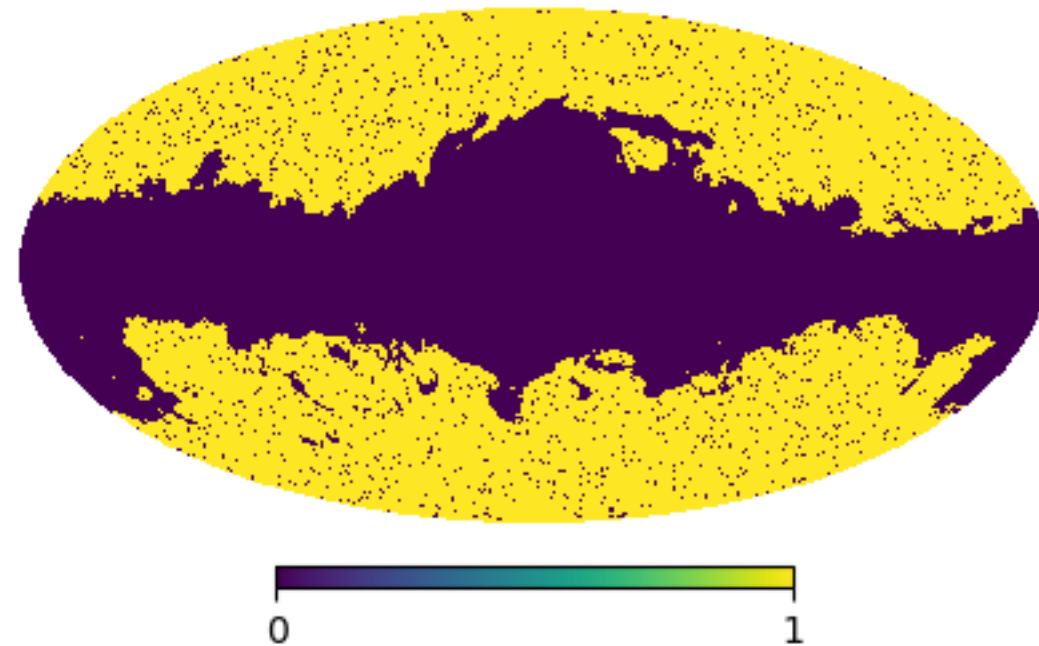
Macro Bin 5, Energy 1.58e+04 MeV



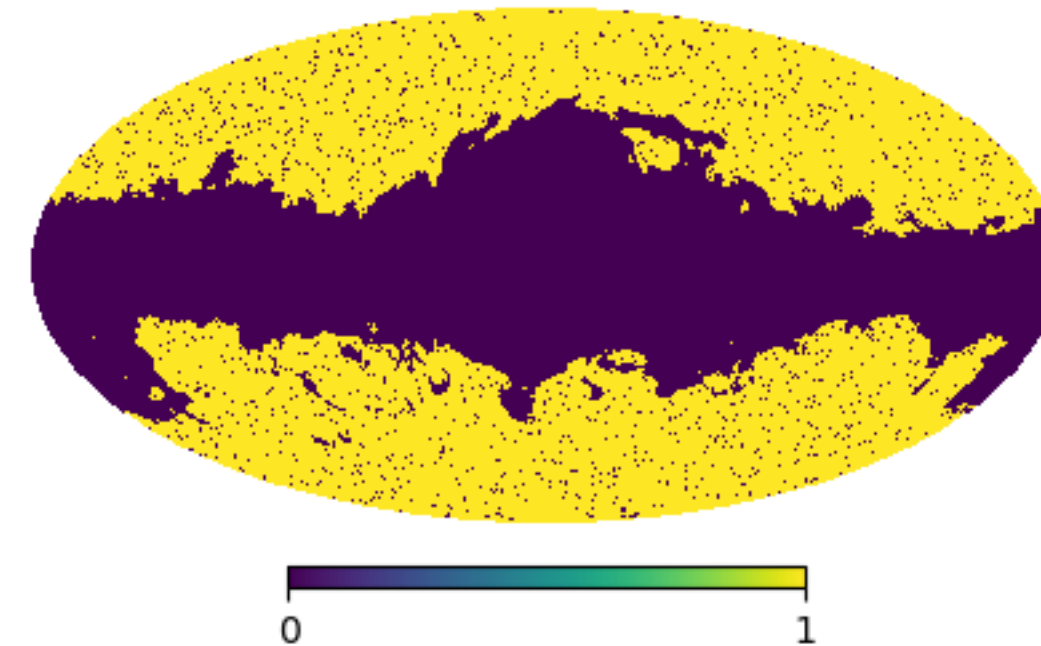
Macro Bin 6, Energy 3.31e+04 MeV



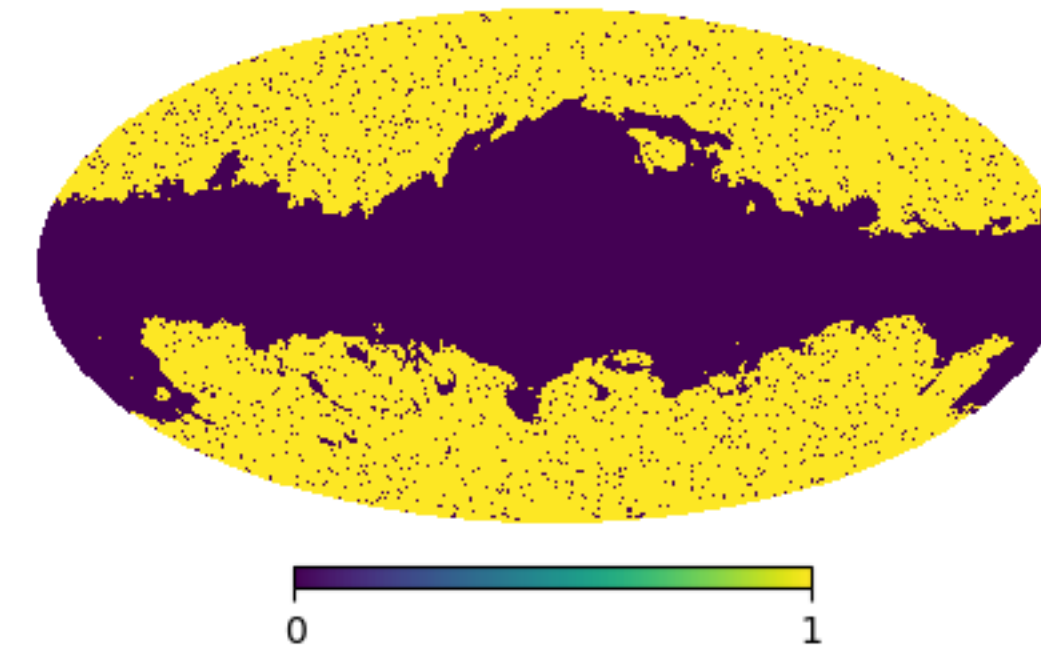
Macro Bin 7, Energy 6.31e+04 MeV



Macro Bin 8, Energy 1.32e+05 MeV



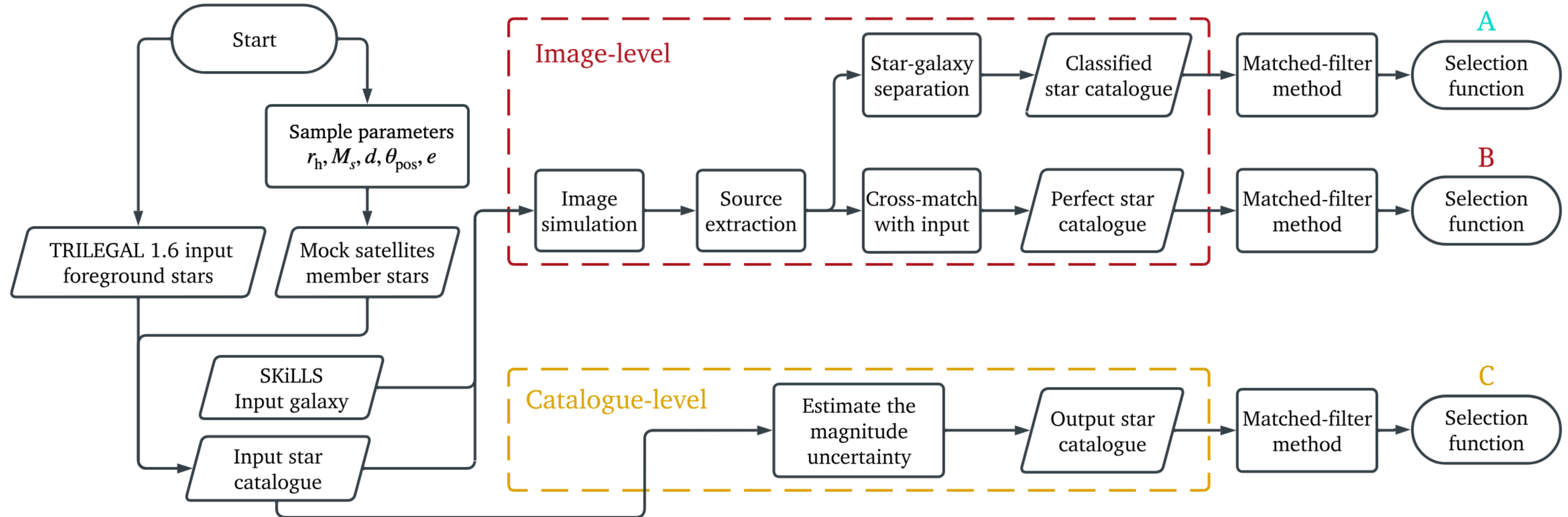
Macro Bin 9, Energy 2.51e+05 MeV



Point source mask radius:

2.1973266 , 1.31626468,
0.73846889, 0.45374015,
0.28324158, 0.28324158,
0.28324158, 0.28324158,
0.28324158, 0.28324158

UFDs selection function: image-level injection-recovery simulations



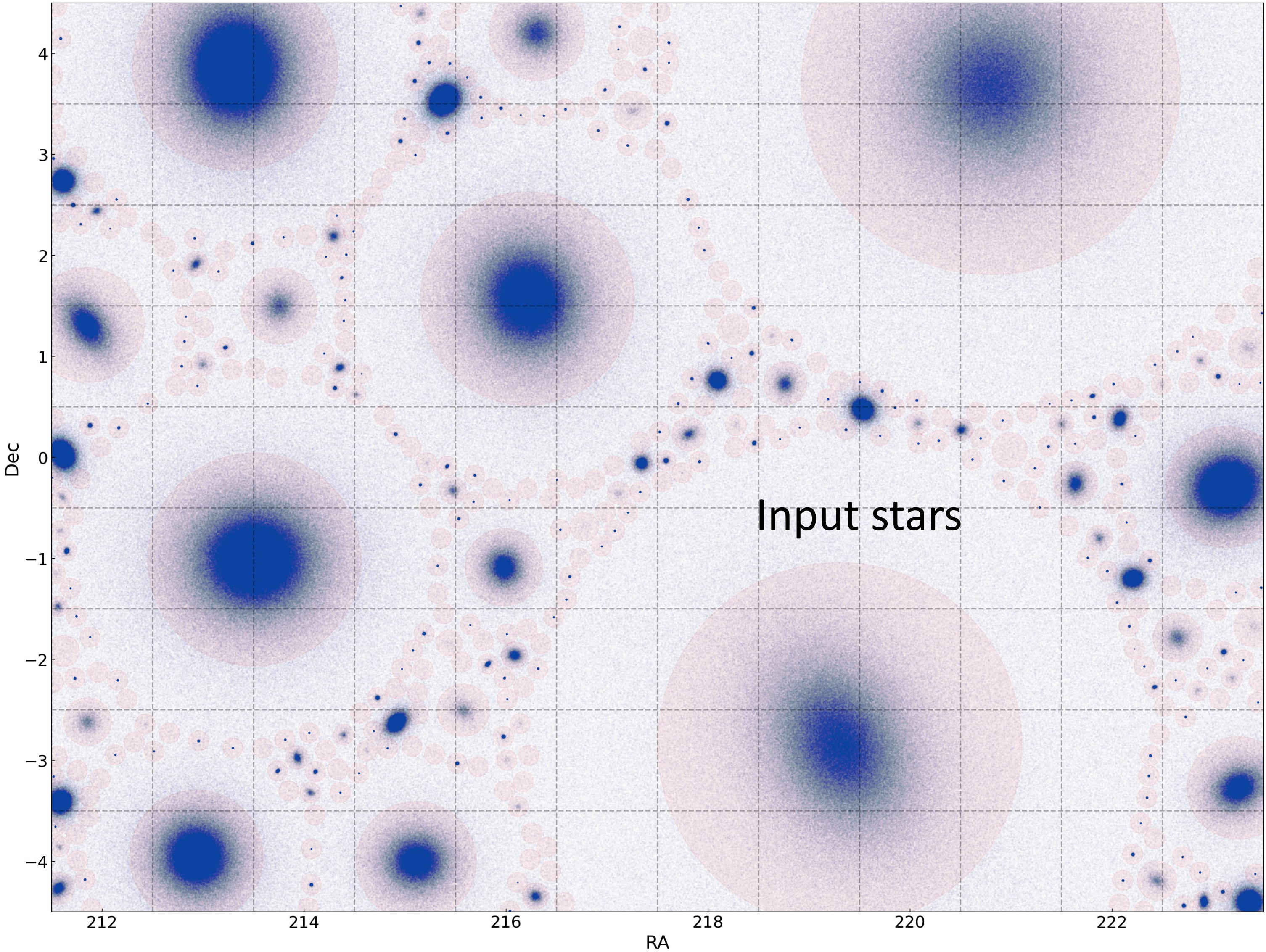
UFDs selection function: Generate mock satellites

- Prepare the injected satellites with parameters

Table 1. Properties of the simulated satellites

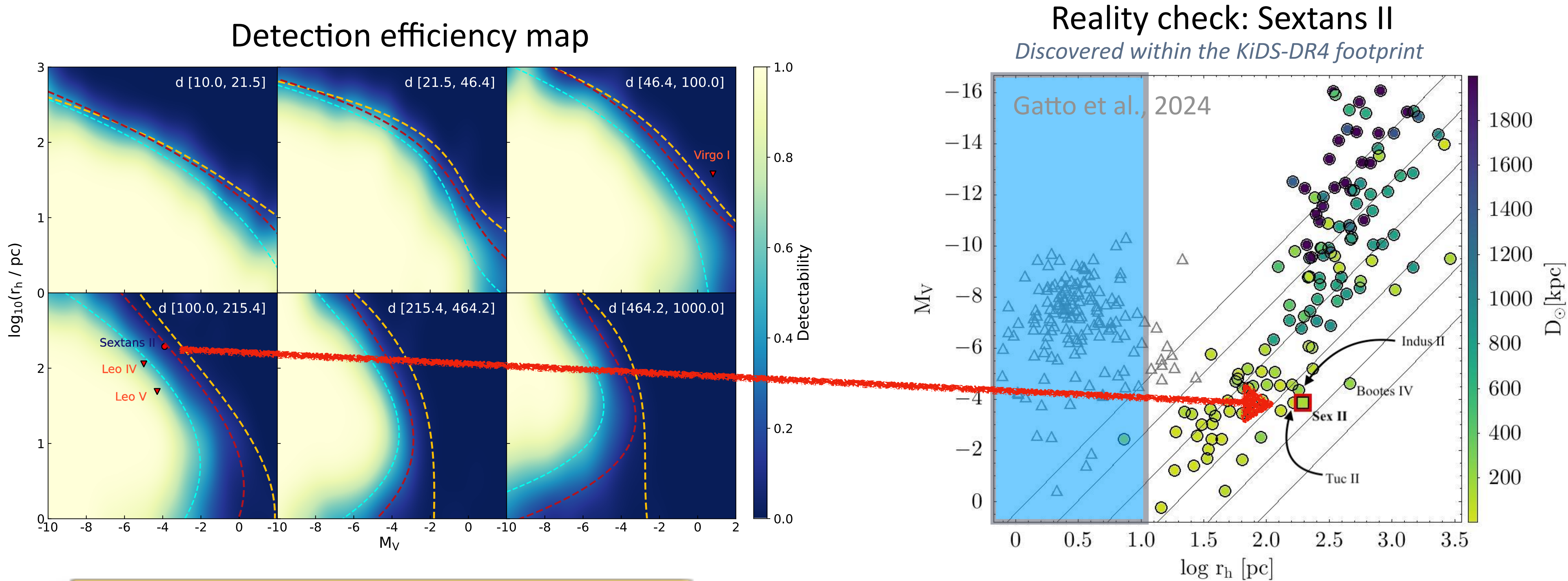
Parameter	Range	Unit	Sampling
Stellar Mass (M_s)	$[10, 10^6]$	$M_\odot$	log
Heliocentric Distance (d)	$[10, 10^3]$	kpc	log
Half-light Radius (r_h)	$[1, 10^3]$	pc	log
Ellipticity (e)	$[0.1, 0.8]$	-	linear
Position Angle (θ_{pos})	$[0, 180]$	deg	linear
Age (τ)	12	Gyr	-
Metallicity (Z)	0.0001	-	-

- Inject satellites
- Draw the satellites
- Add the foreground stars (from TRILEGAL 1.6)



Local substructure: UFDs detection efficiency & selection function (smoothed)

A realistic selection function is essential for interpreting the satellite census and indirect-search target samples.



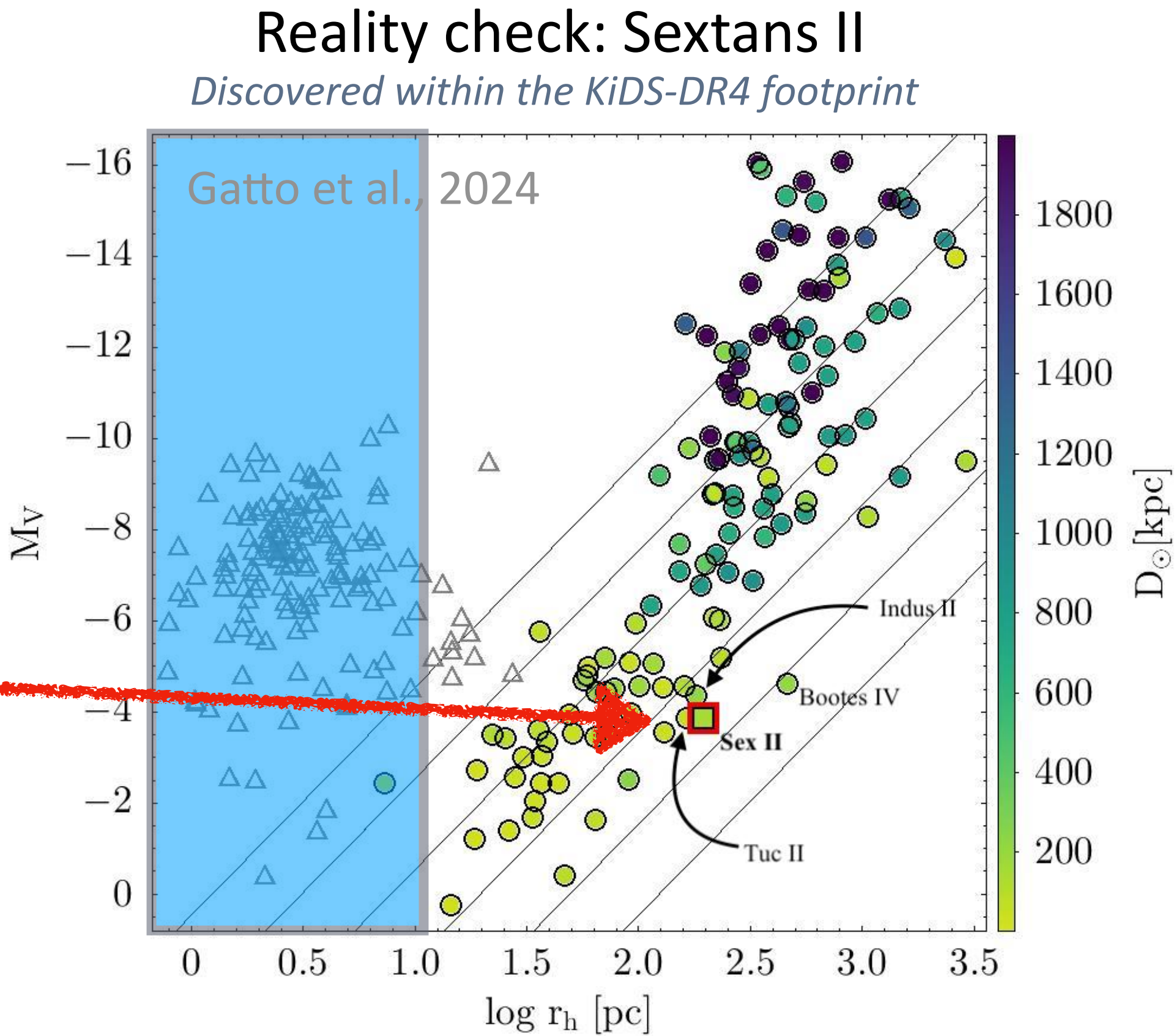
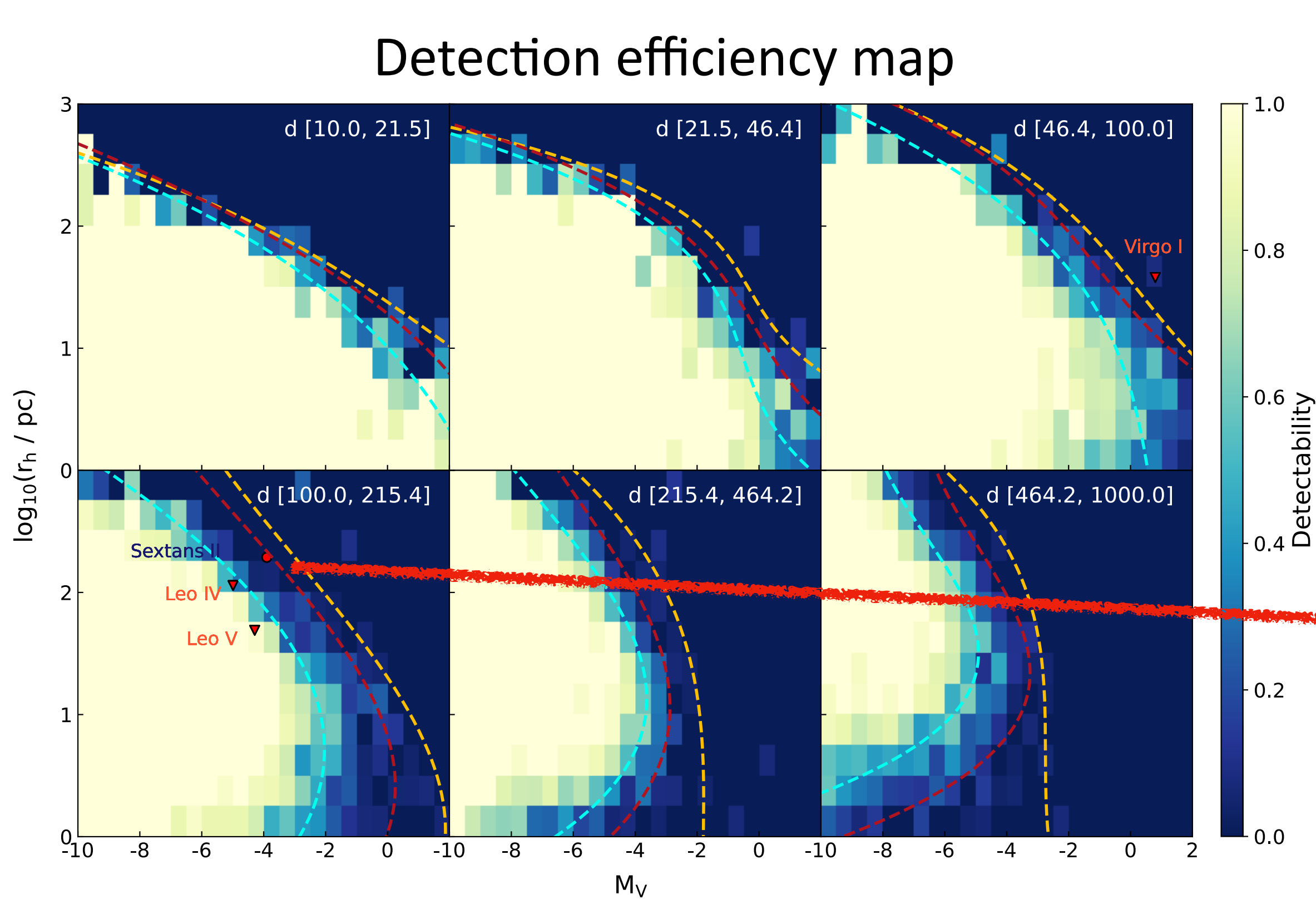
Simulation type

- Catalogue-level
- Image-level, ideal star selection
- Image-level, realistic SG separation

Catalogue-level	71.3%
Image-level, ideal stars	48.7%
Image-level, realistic SG	10.8%

Local substructure: UFDs detection efficiency & selection function (binned)

A realistic selection function is essential for interpreting the satellite census and indirect-search target samples.



Simulation type

- Catalogue-level
- Image-level, ideal star selection
- Image-level, realistic SG separation

Catalogue-level

71.3%

Image-level, ideal stars

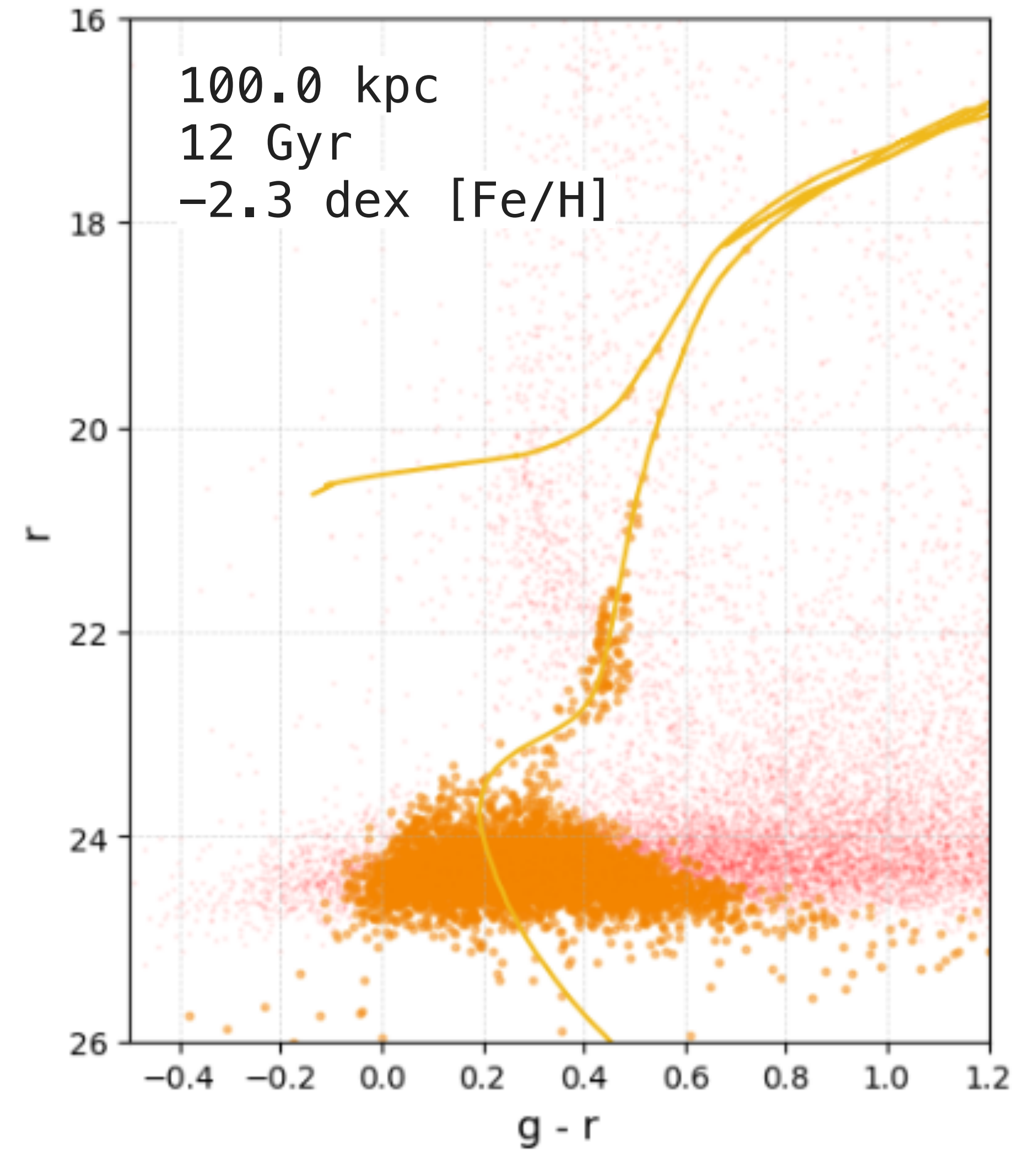
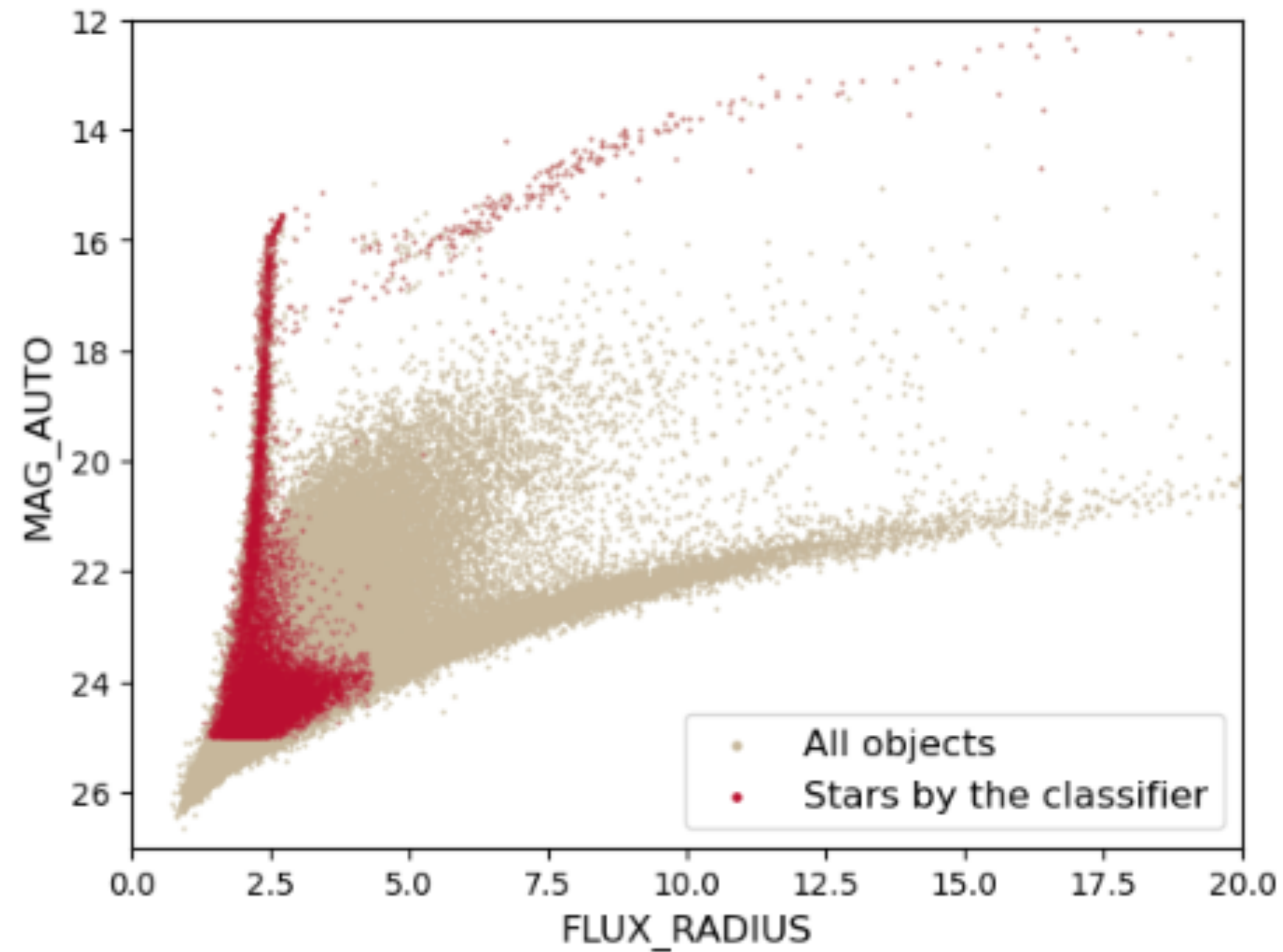
48.7%

Image-level, realistic SG

10.8%

Matched-filter method

- Star-galaxy separation;
- Select all stars consistent with an old, metal-poor isochrone shifted to some distances;



Matched-filter method

- Project the stars meet colour criteria onto the tangent plane, and bin them spatially;
- Smooth the 2D stellar density map with different sizes Gaussian kernels ρ_{sm} ;

Convolve the map with 2D top hat filter to get the local stellar density ρ_{loc} ;

Significance map:
$$s = \frac{\rho_{\text{sm}} - \rho_{\text{loc}}}{\sqrt{\langle \rho_{\text{loc}} \rangle^2 - \langle \rho_{\text{loc}}^2 \rangle}}$$

